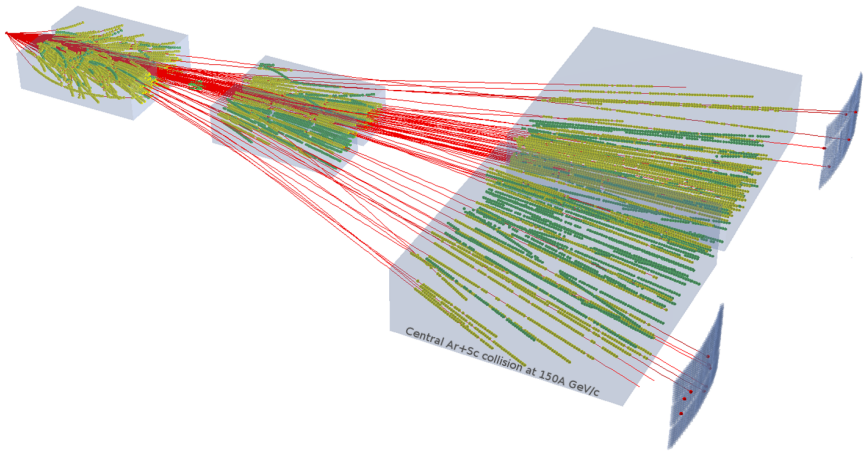
News from NA61/SHINE at CERN SPS

Magdalena Kuich

for the NA61/SHINE collaboration



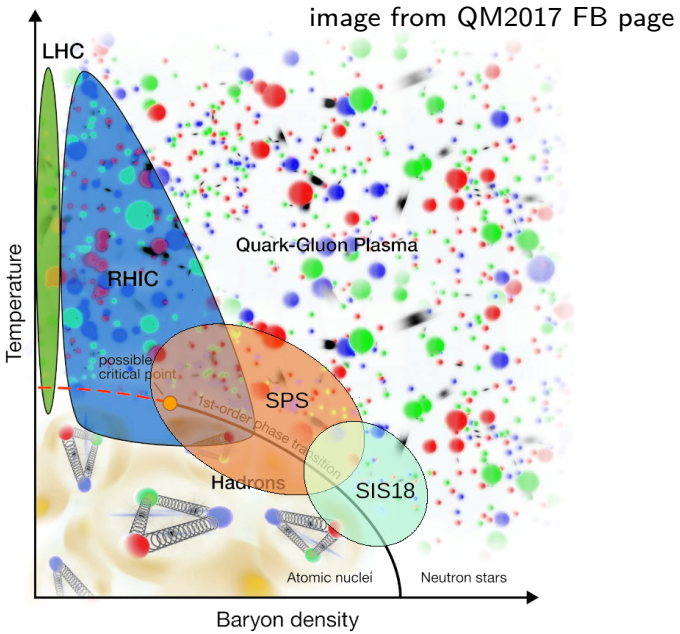
Beam energy scan in large systems - workshop

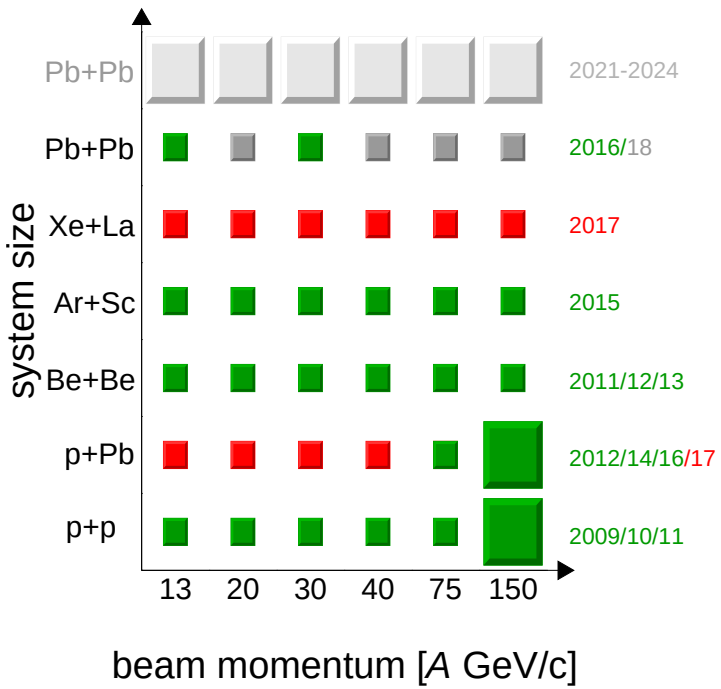
Brookhaven National Laboratory, June 20-23 2017

2D phase space scan by NA61/SHINE

NA61/SHINE experiment performs 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter in **baryon density and temperature**

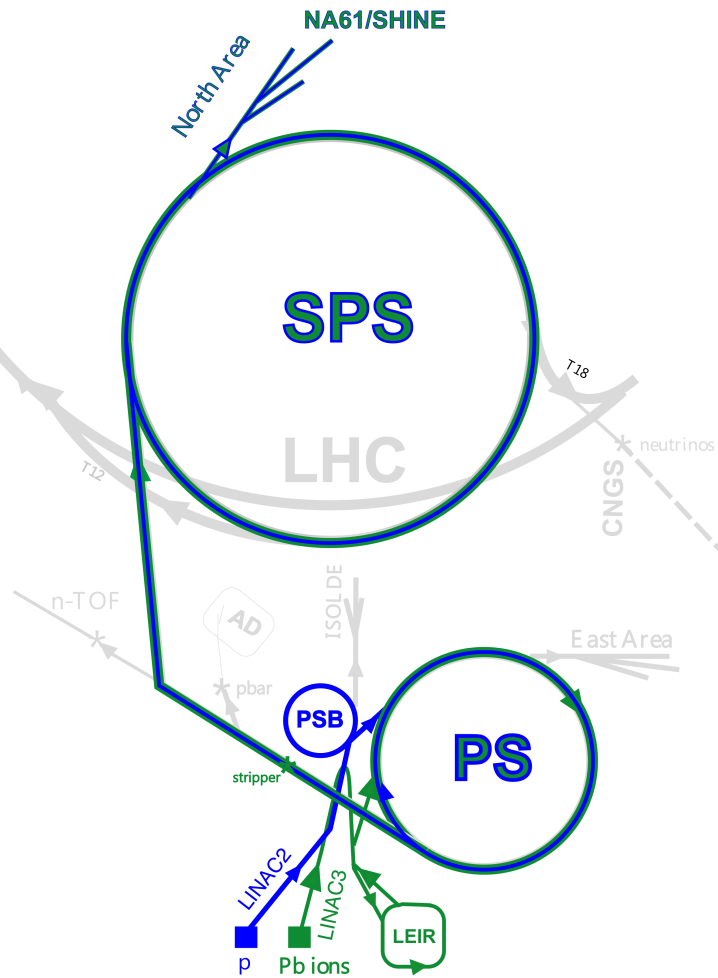
Research was motivated by NA49 results on onset of deconfinement
NA61/SHINE and STAR BES run in parallel

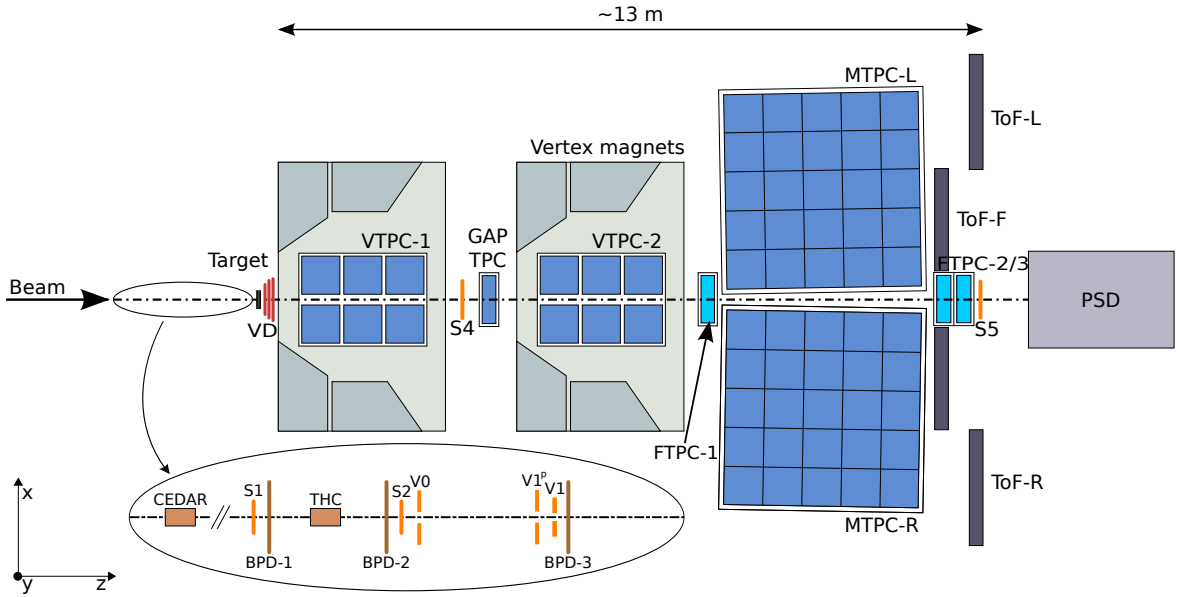




- Particle spectra → study of **onset of deconfinement**
- Fluctuations → search for the **critical point**

NA61/SHINE spectrometer

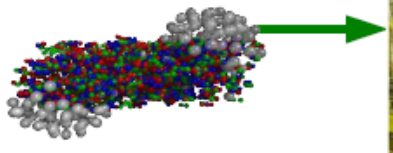


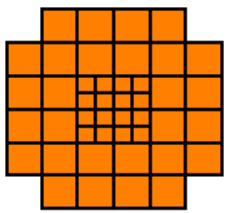


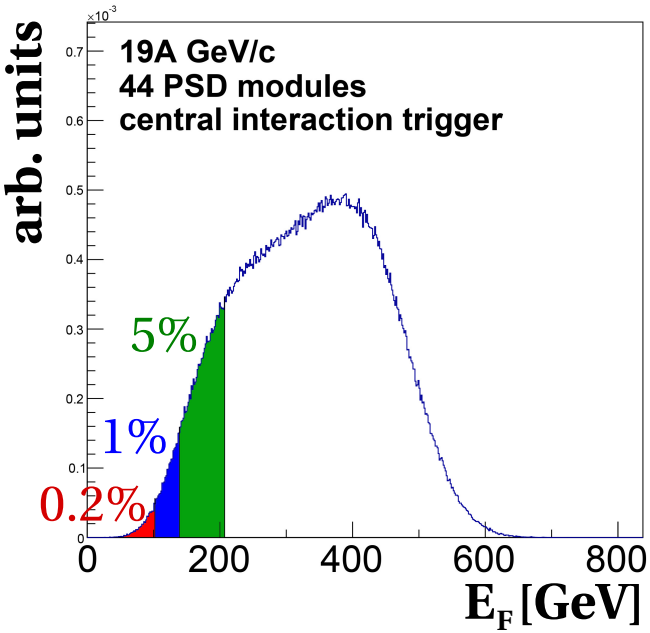
- **Fixed target experiment located at the SPS accelerator**
- Beams:
  ions (Be, Ar, Xe, Pb) $p_{\text{beam}} = 13A - 150A$ GeV/c
  hadrons (π, K, p) $p_{\text{beam}} = 13 - 400$ GeV/c
  $\sqrt{s_{\text{NN}}} = 5.1\text{–}16.8\ (27.4)$ GeV
- **Large acceptance hadron spectrometer** – coverage of the full forward hemisphere, down to $p_{\text{T}} = 0$
- **Centrality** selection based on **forward energy** (projectile spectators) measured in PSD

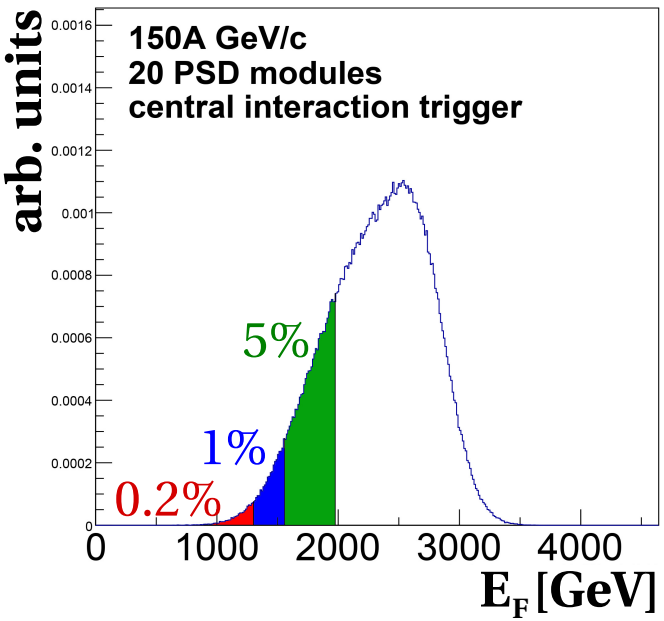
Event selection based on forward energy measurements

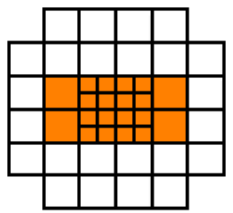
- **Event (centrality) selection** is done using **the forward energy**(E_F) dominated by energy of projectile spectators
- Examples of event selection using E_F for Ar+Sc:





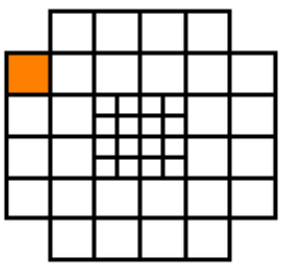


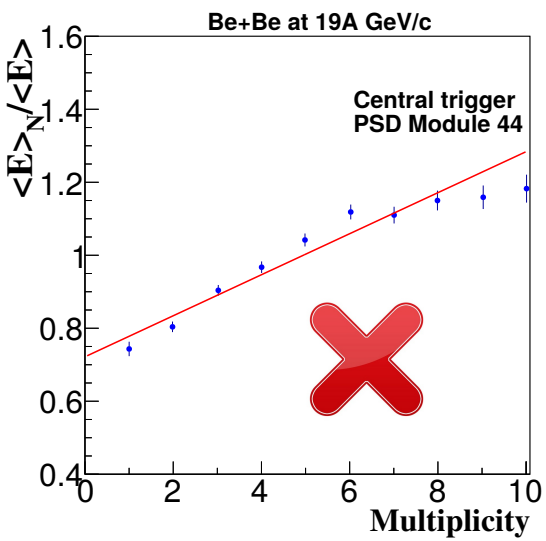


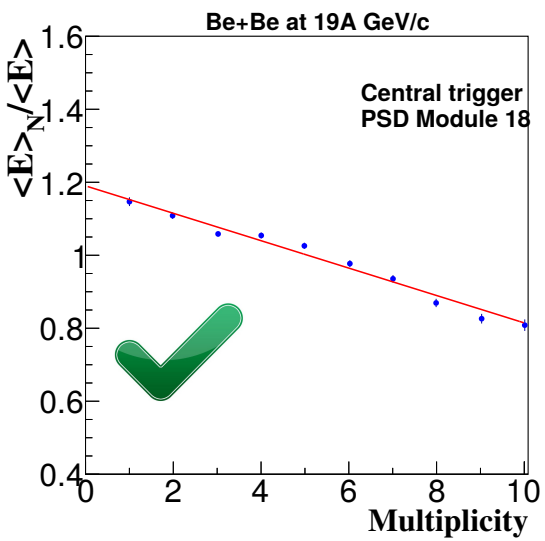


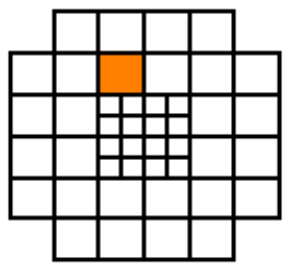
Event selection based on E_F measurements

- Due to different magnetic field setting and PSD position for various beam momenta, selection of PSD modules for E_F calculation depends on reaction
- The module selection is based on correlation between energy deposit in a module and track multiplicity in TPC
- Negative correlation implies dominance of spectators hitting the module



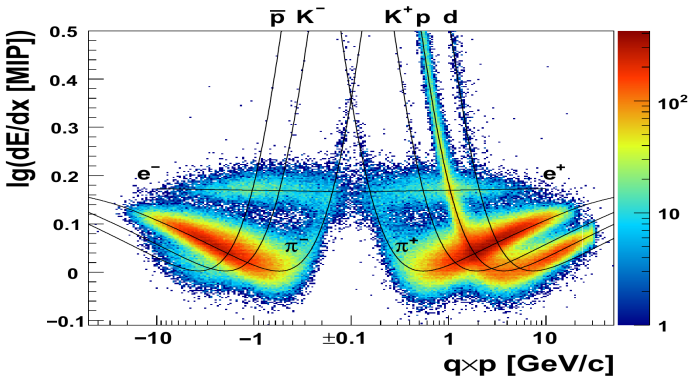


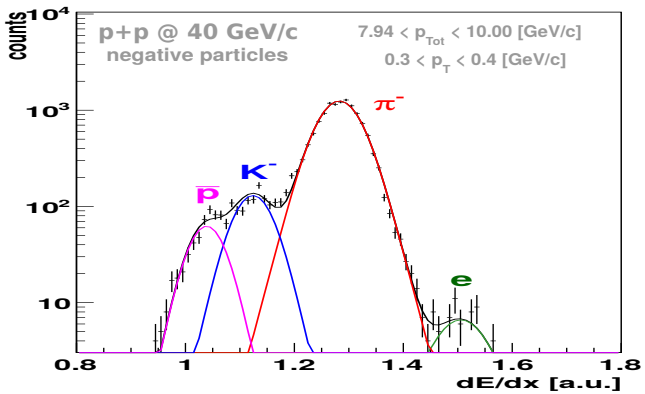


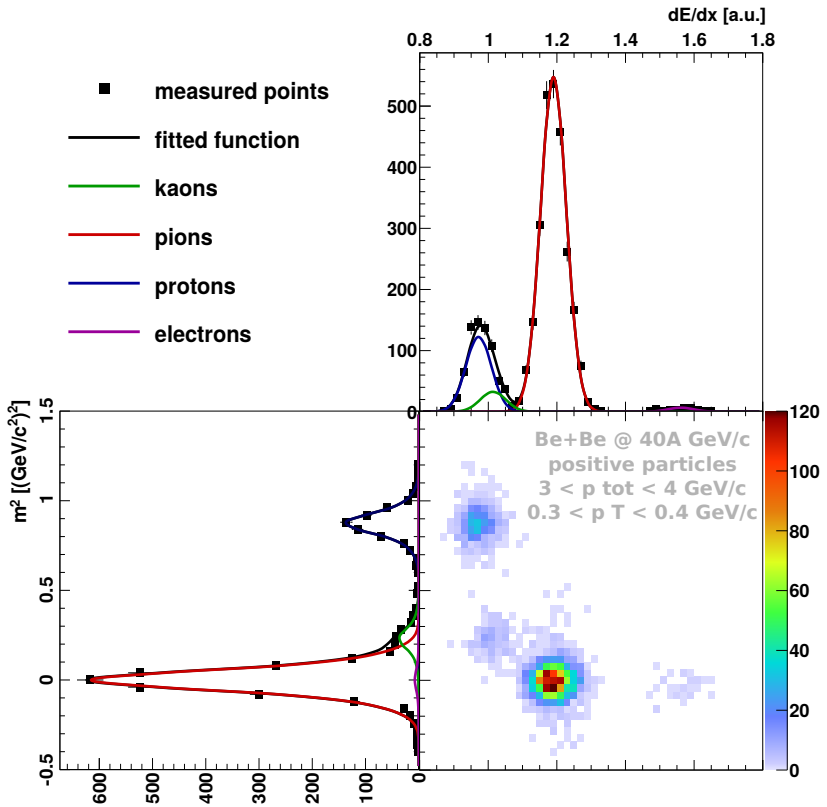


Examples of correlation between energy in a PSD module and track multiplicity in TPC for ^{7}Be+^{9}Be collisions 19A GeV/c

Particle identification

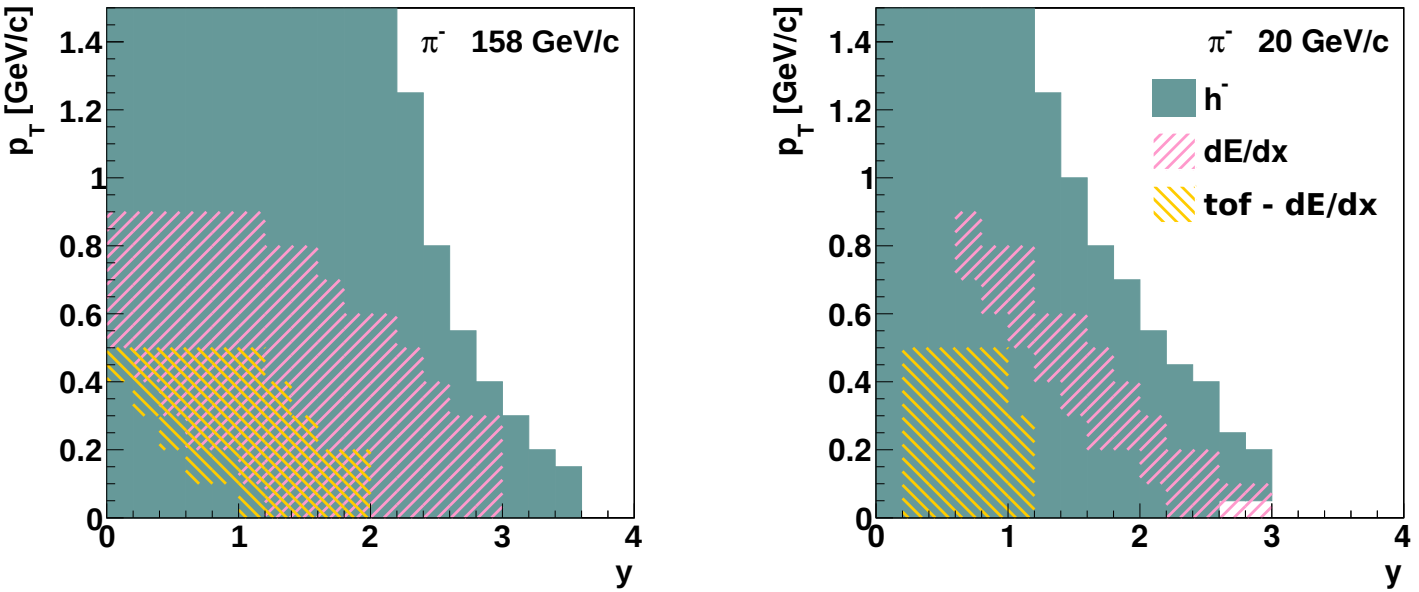






- *dE/dx* method estimates number of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ using an energy loss measurement
- *tof-dE/dx* method estimates number of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ using an energy loss and a particle time of flight measurements

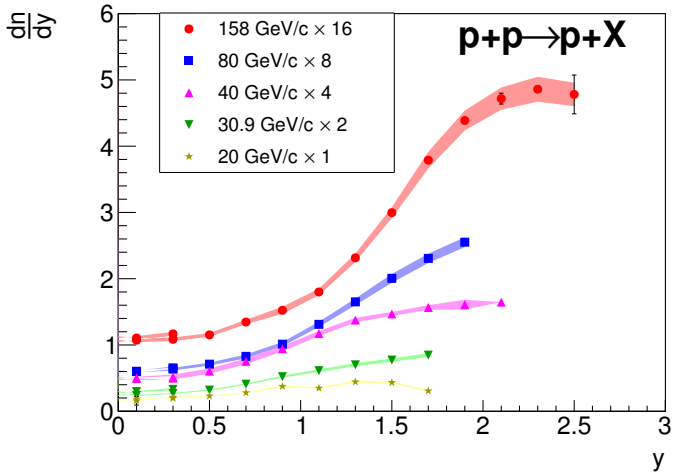
Particle identification



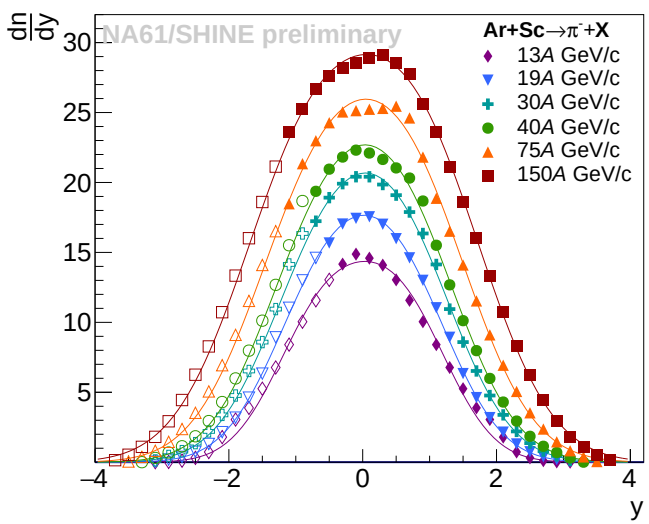
- h^- method estimates number of π^- in large phase space based on fact that majority of negatively charged particles produced in p+p and A+A collisions are π^-
- Non–π^- contamination is corrected for by models (typically EPOS 1.99)
- All methods are complementary, allow for cross check and covering the large part of the phase space
- Final results stand for primary particles produced in strong and electromagnetic processes, they are corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

Example of results

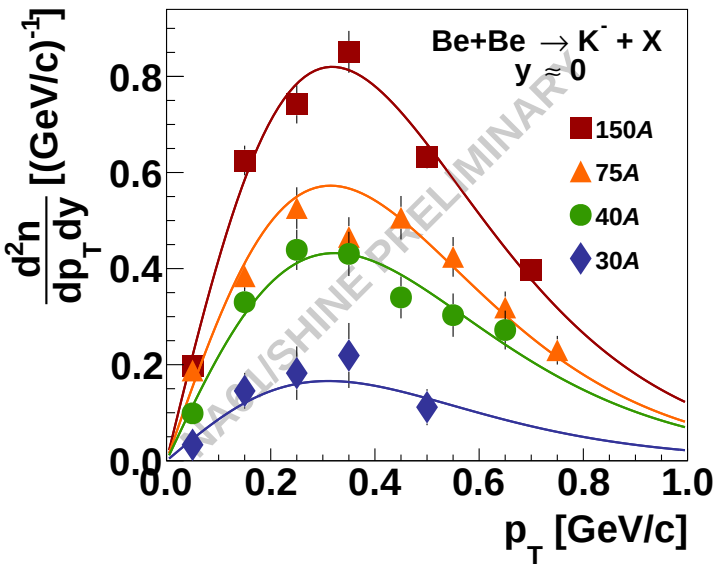
dE/dx and *tof-dE/dx*



h$^-$



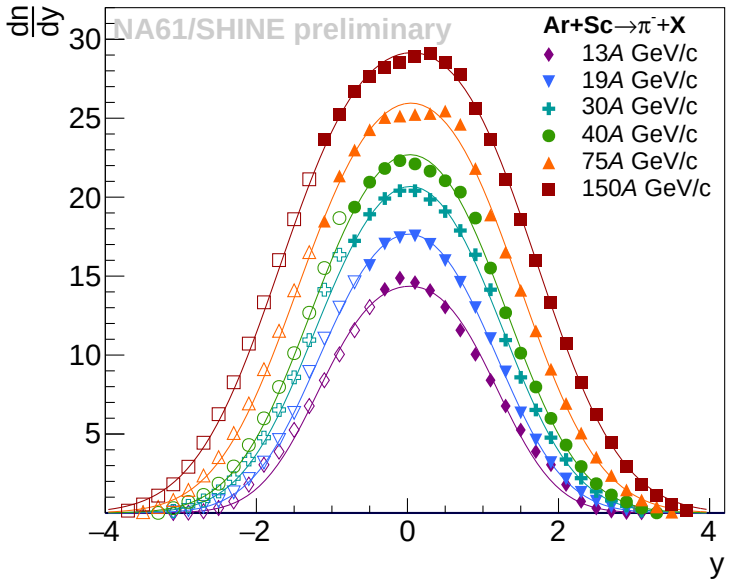
tof-dE/dx



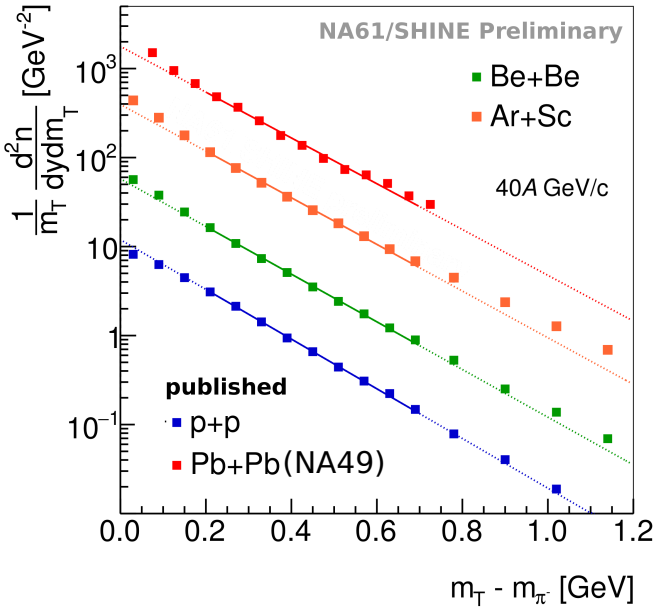
- Charged hadrons – $K^{\pm}$, $\pi^{\pm}$, p, $\overline{\text{p}}$ – measured as a function of y and p_T
- $K^{\pm}$ well identified in mid-rapidity and in p_T down to 0
- π^- spectra measured in large acceptance in full forward hemisphere

π^- spectra from the two-dimensional scan

Collision energy dependence



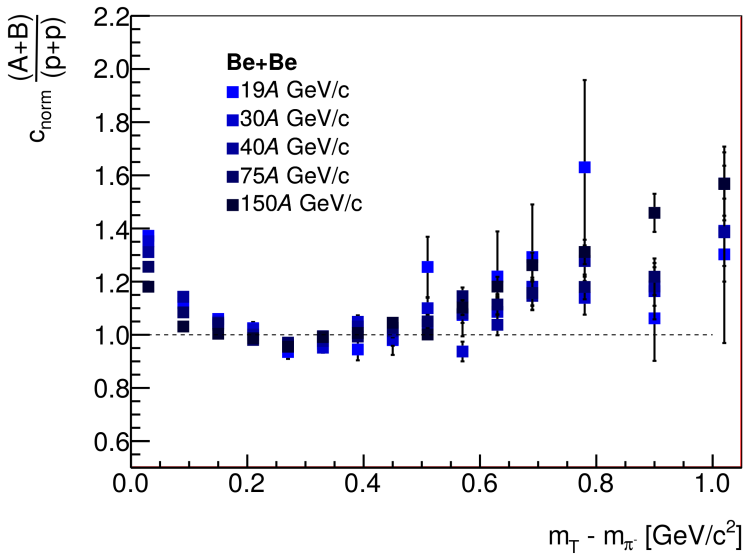
System size dependence

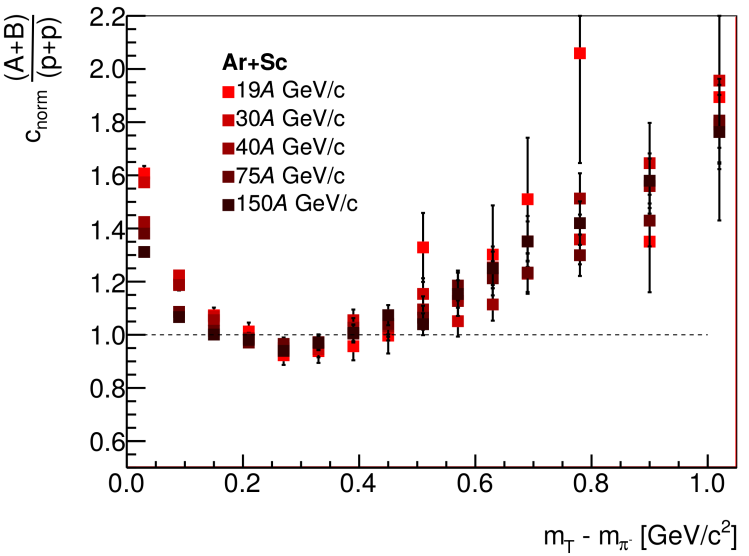


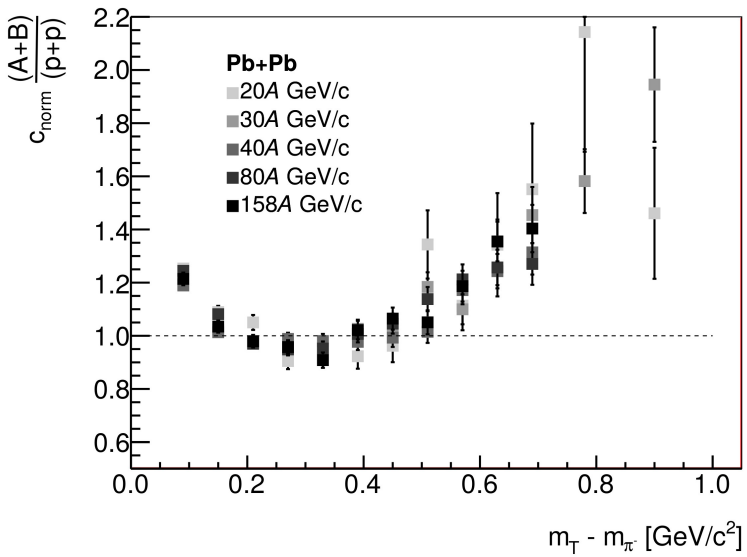
- π^- spectra measured in large acceptance: p_T down to 0, in full forward hemisphere
- Rapidity spectra approximately gaussian, independently of the collision energy
- Large detector acceptance allows to obtain 4π pion multiplicity from the data and extrapolation (for details see arXiv:1612.01334)
- m_T spectra in p+p $\approx$ exponential
- m_T spectra in larger systems (central collisions) deviate from the exponential shape

Only statistical uncertainties shown

Energy and system size dependence of m_T spectra

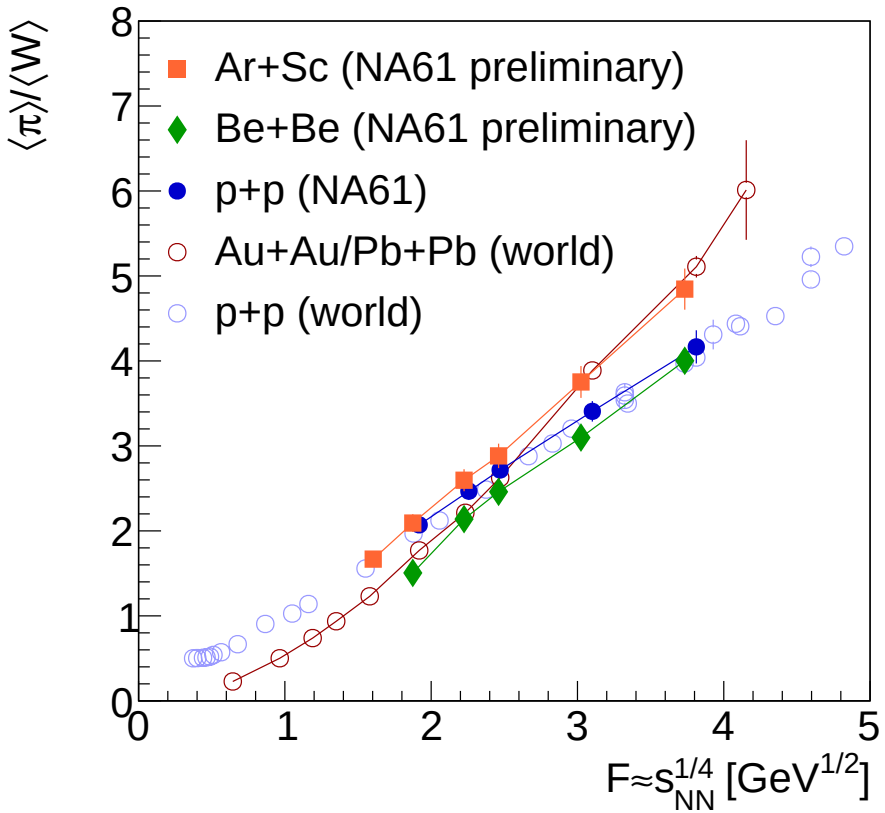






- m_T shape differs significantly between p+p and A+A
  - clear system size dependence
  - small energy dependence
  - the effect possibly associated to transverse collective flow

Study of the onset of deconfinement: kink



$\langle\pi\rangle$ – mean π multiplicity in full acceptance

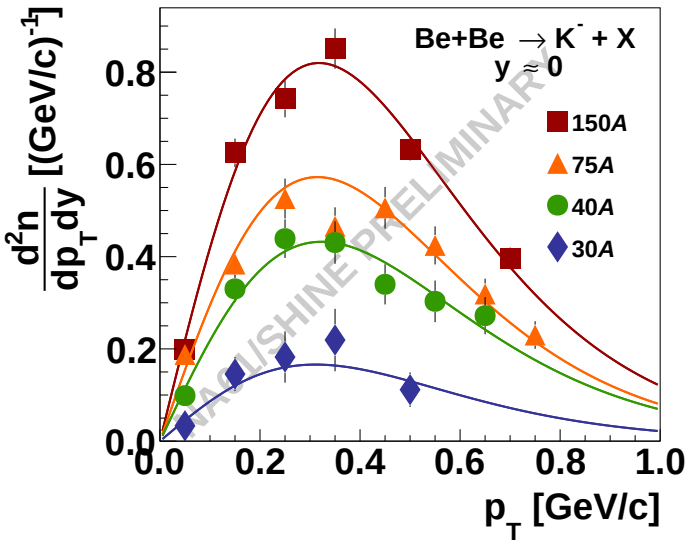
$\langle W\rangle$ – mean number of wounded nucleons

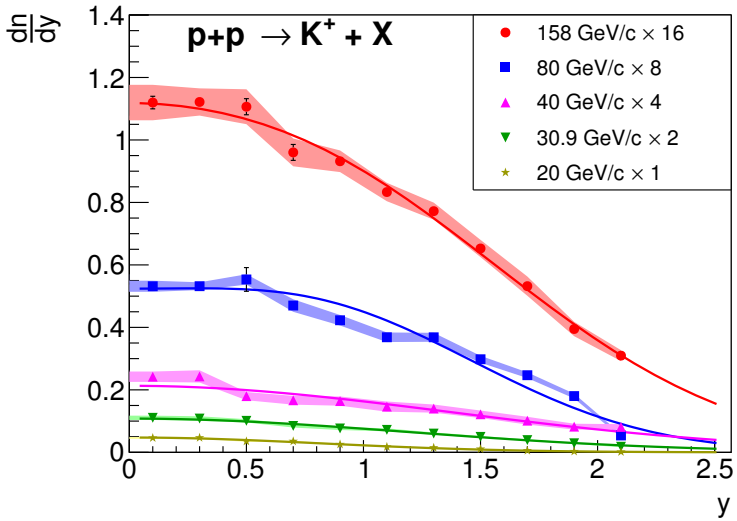
$$F \equiv \left[\frac{(\sqrt{s_{NN}}-2m_N)^3}{\sqrt{s_{NN}}}\right]^{1/4} \approx s_{NN}^{1/4}$$

- The slope of energy dependence for heavier systems is larger than for lighter systems at high SPS energies
- Statistical model with phase transition (SMES[a]) predicts increase of the slope – **KINK** – of $\langle\pi\rangle/\langle W\rangle$ in QGP due to the larger number of degrees of freedom in comparison to HRG

[a] Acta Phys. Pol. B30 (1999) 2705

Study of onset of deconfinement: step and horn



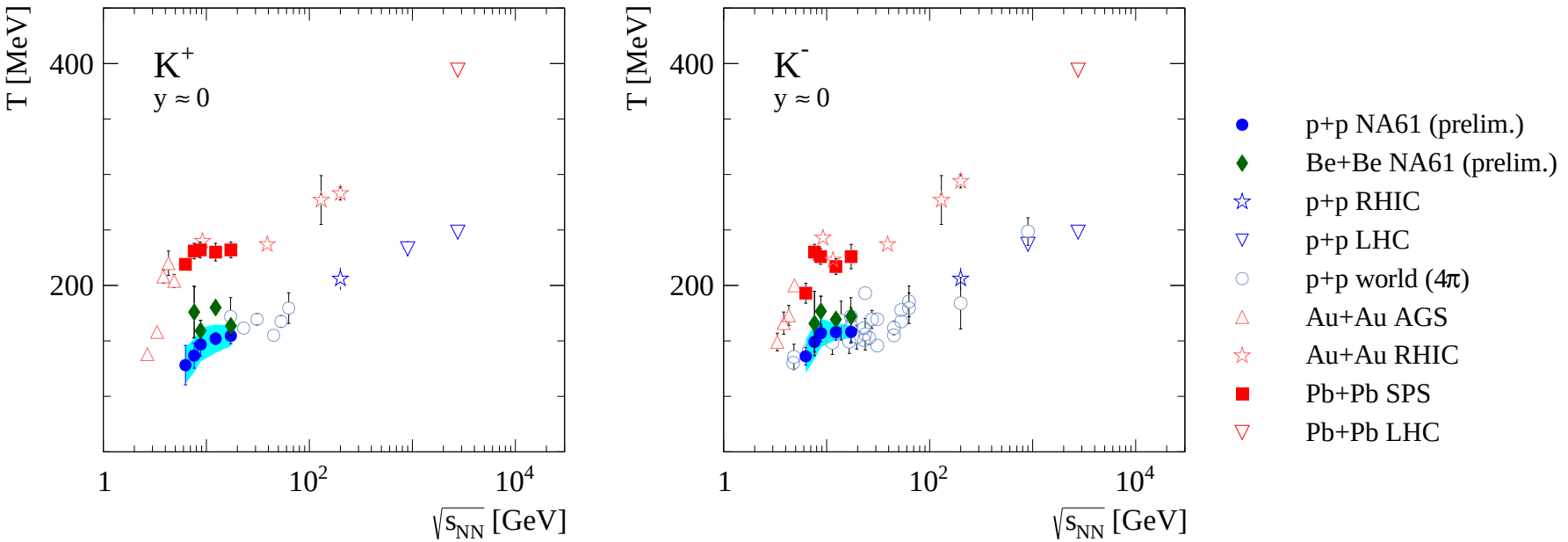


- $K^{\pm}$ spectra in p_T are are fitted with exponential function

$$\frac{d^2n}{dp_T dy} = \frac{S\ p_T}{T^2 + T\ m_K}\ exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$$

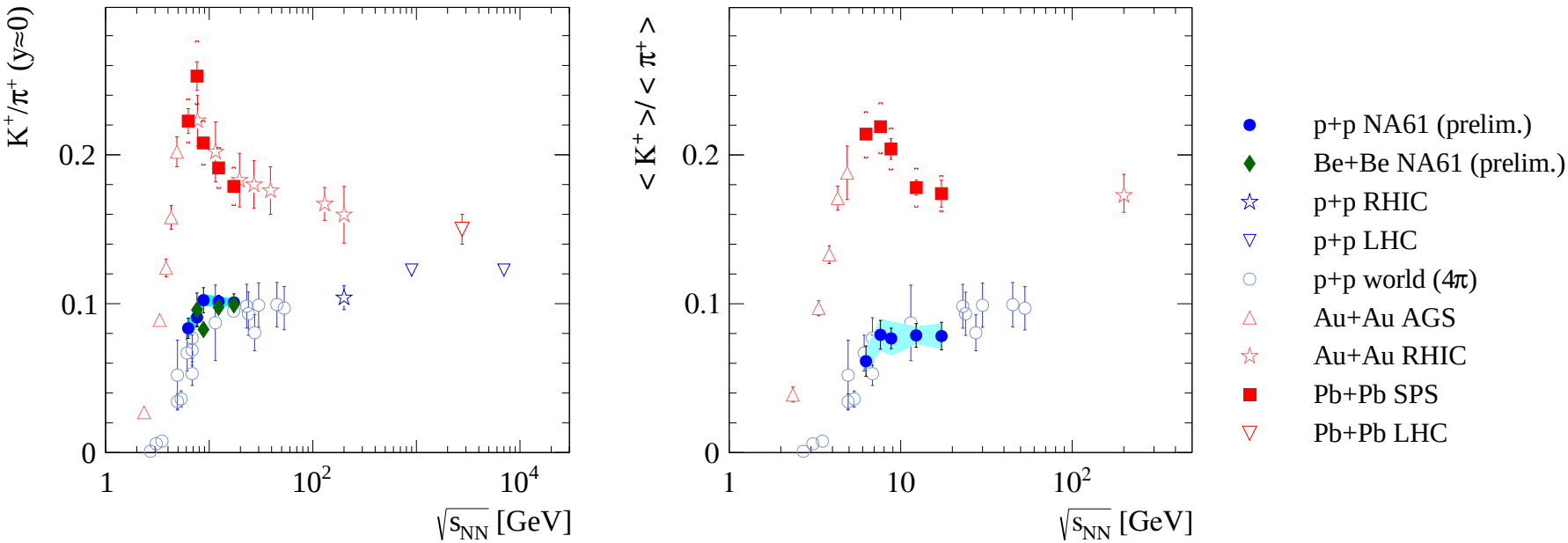
- The fit yield the inverse slope parameter, T, and is used to extrapolate spectra up to $p_T = 1$ GeV/c
- $K^{\pm}$ spectra in y reflected to backward hemisphere to obtain $< K^{\pm} >$

Study of onset of deconfinement: step



- Plateau – **STEP** – in the inverse slope parameter of m_T spectra in Pb+Pb collisions observed. It is expected for the onset of deconfinement due to mixed phase of HRG and QGP (SMES)
- Qualitatively similar structure is visible in p+p and it seem to emerge in Be+Be
- Be+Be slightly above p+p

Study of onset of deconfinement: horn



- Rapid changes in K^+/π^+ – **HORN** – were observed in Pb+Pb collisions. It was predicted (SMES) as a signature of onset of deconfinement too
- Plateau like structure (maybe a shadow of horn structure) visible in p+p
- Be+Be very close to p+p

Event – by – event fluctuations

Intensive quantities

A ratio of two extensive quantities ($\sim$ volume) is an intensive quantity e.g.:

$$\omega[A] = \frac{\langle A^2 \rangle - \langle A \rangle^2}{\langle A \rangle},$$

where A stands for an extensive event quantity.

- independent of V
- depends on fluctuations of V
- $\omega = 1$ for Poisson distribution

In statistical model (IB-GCE) $\omega_i = \frac{Var(a)}{\langle a \rangle} + \langle a \rangle \frac{Var(V)}{\langle V \rangle}$, where a - particles produced in a system with fixed V

Strongly intensive quantities

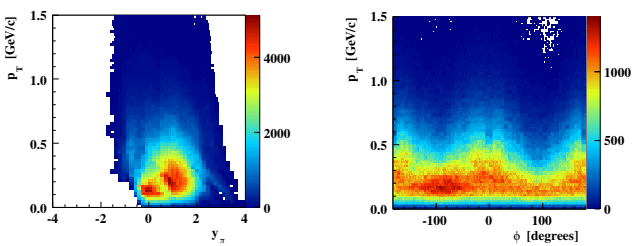
Special combination of extensive quantities can be a strongly intensive measure e.g.:

$$\Sigma[A, B] = \frac{1}{C_\Sigma}\Big[\langle B \rangle \omega_A + \langle A \rangle \omega_B - 2\Big(\langle AB \rangle - \langle A \rangle \langle B \rangle\Big)\Big]$$

- independent of V and fluctuations of V
- normalization chosen such that $\Sigma[A, B] = 1$ for independent particle model and quantity is dimensionless
- $\Sigma[A, B] = 0$ in the absence of fluctuations

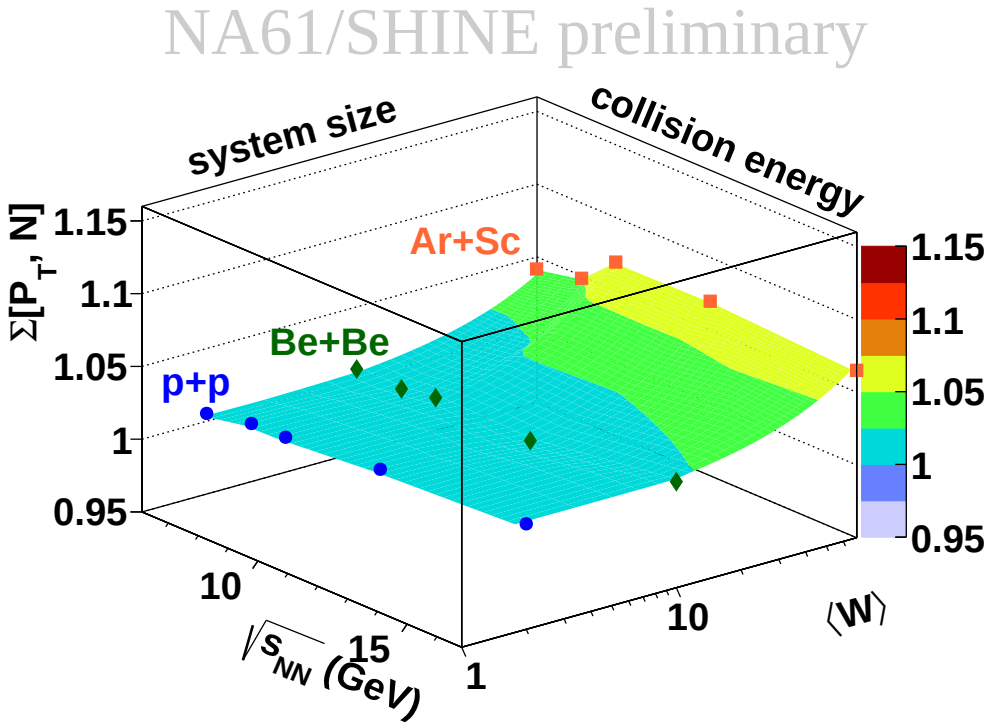
NA61/SHINE **acceptance**

The acceptance for event–by–event fluctuations was selected to the region were the reconstruction efficiency is higher than 90%. Selection was based on MC simulation in three-dimensional bins of rapidity, azimuthal angle and transverse momentum.



Acceptance example for 150A GeV/c

Search for critical point: P_T and N fluctuations



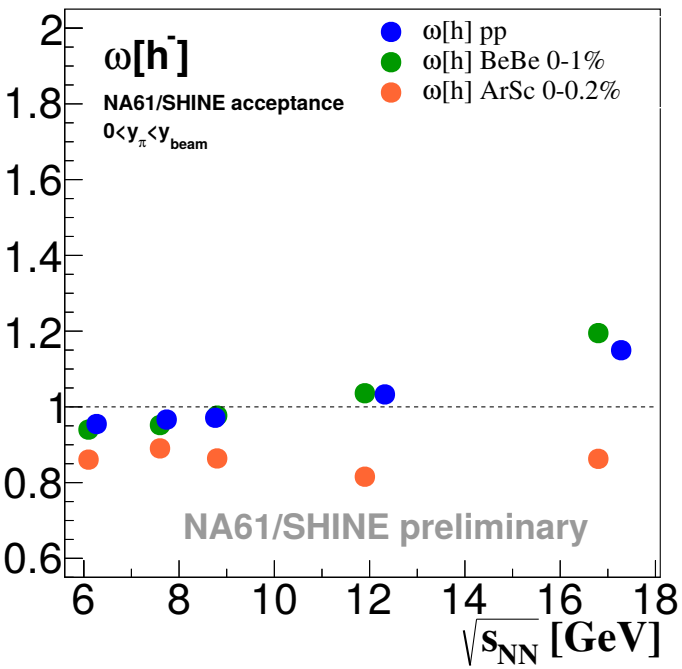
Negatively charged hadrons in central A+A and inelastic p+p

- $\sim$5% monotonic increase of $\Sigma[P_T, N]$ with the system size
- **No indication for critical point so far**

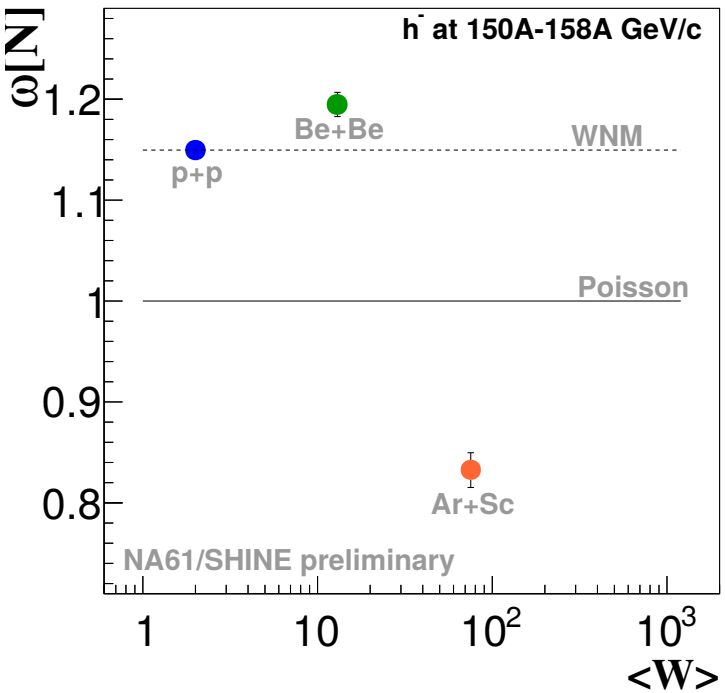
$\Sigma[P_T, N] = 0$ for $N = \text{const.}$, $P_T = \text{const.}$
$\Sigma[P_T, N] = 1$ for Independent Particle Model

Energy and system size energy dependence of $\omega[N]$

Collision energy dependence

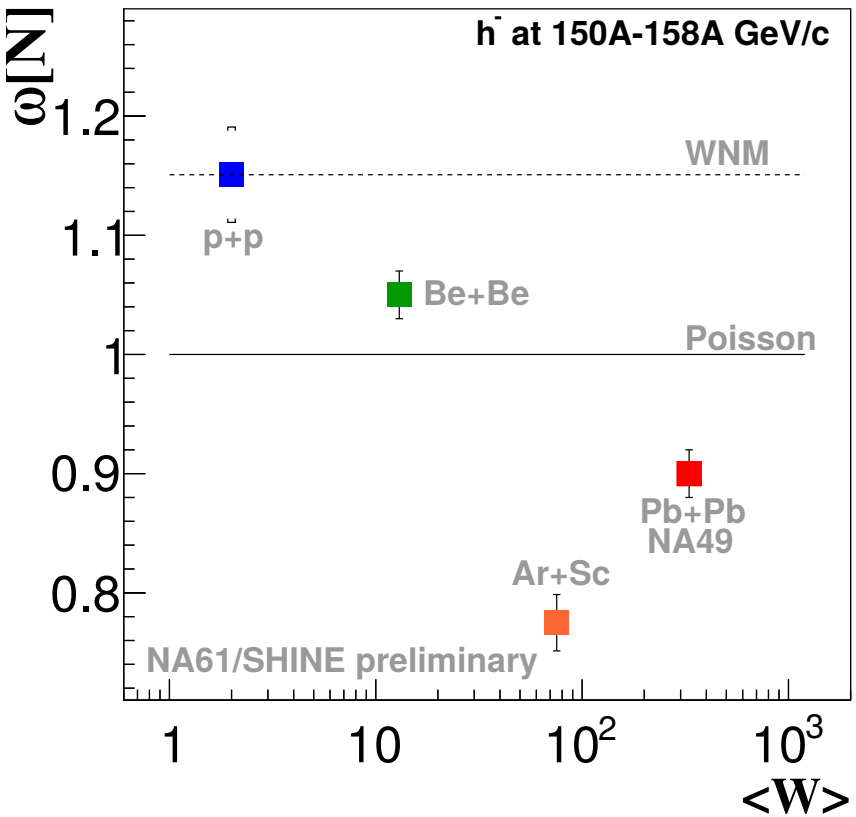


System size dependence



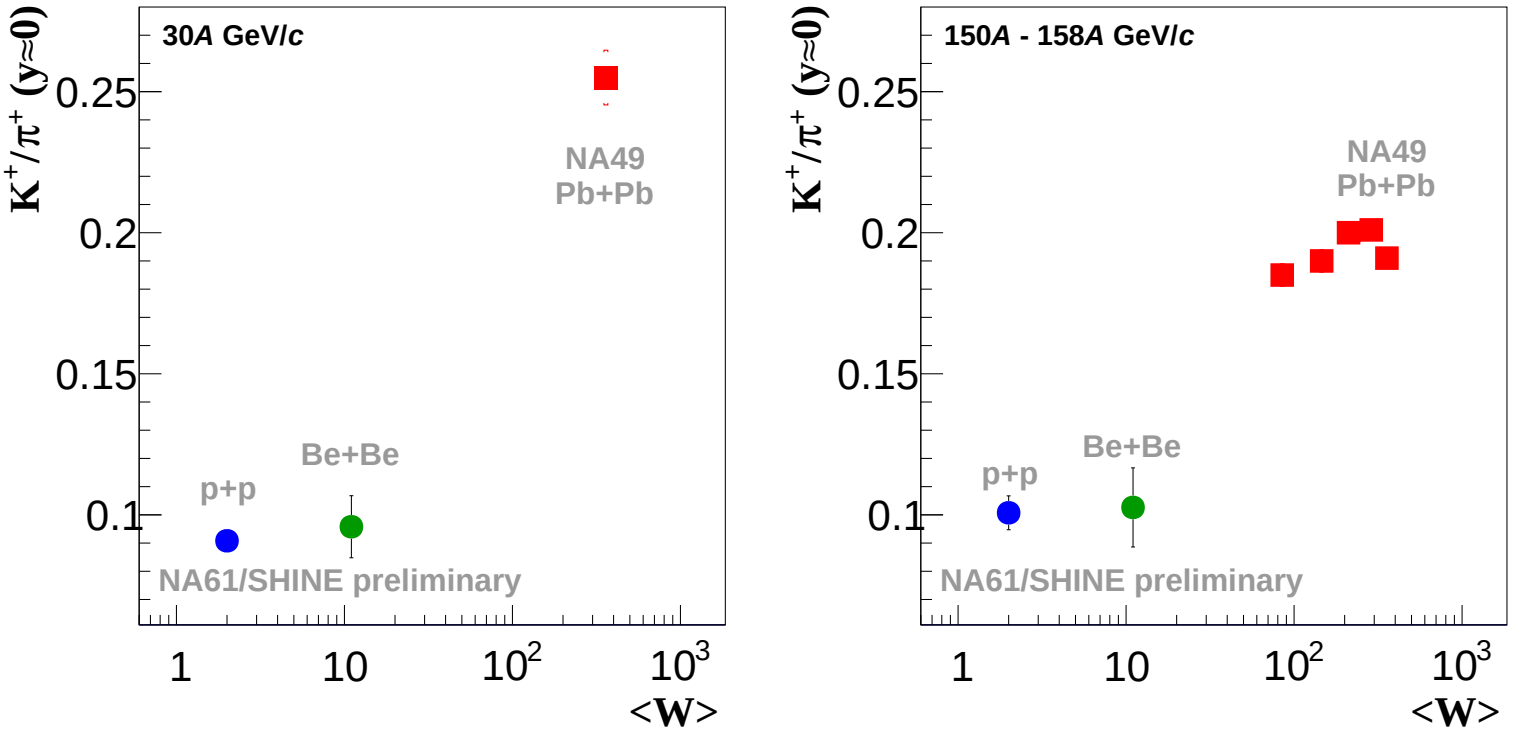
- $\omega[N]$ decreases with the system size what is **not expected** in **Ideal Boltzmann Grand Canonical Ensemble** (Poisson) or the **Wounded Nucleon Model** (p+p)
- Be+Be results close to p+p and significantly higher than Ar+Sc

Comparison with NA49



- NA61/SHINE data were analysed in NA49 acceptance what reduces the mean multiplicity of negatively charged hadrons by 30% for 150A GeV/c and up to 50% for 20A GeV/c (for detail see EPJC 76 11: 635)
- Significant difference between light and heavy systems remains

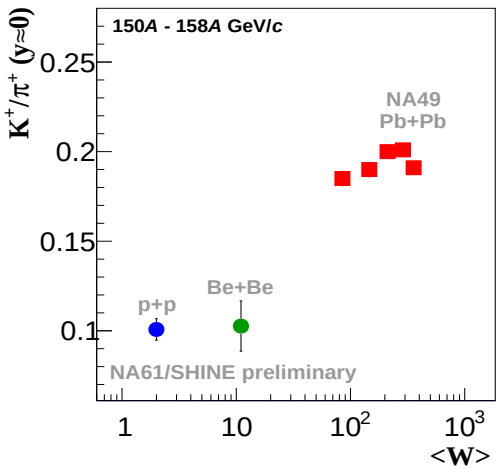
Looking back to particle yields ratios...

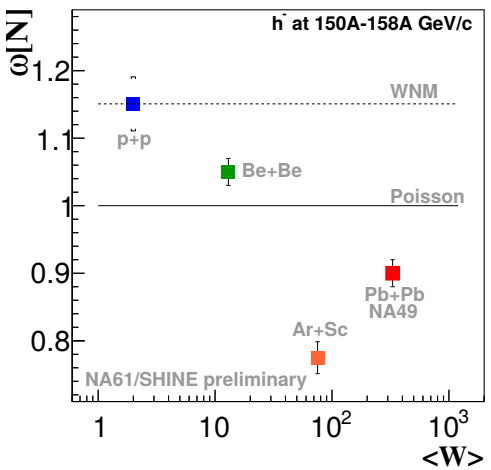


- Surprisingly Be+Be results are very close to p+p independent of collision energy
- As in the case of $\omega[N]$ data suggest a jump between light and heavy systems
- Waiting on the edge of my sit for Ar+Sc results!

Summary

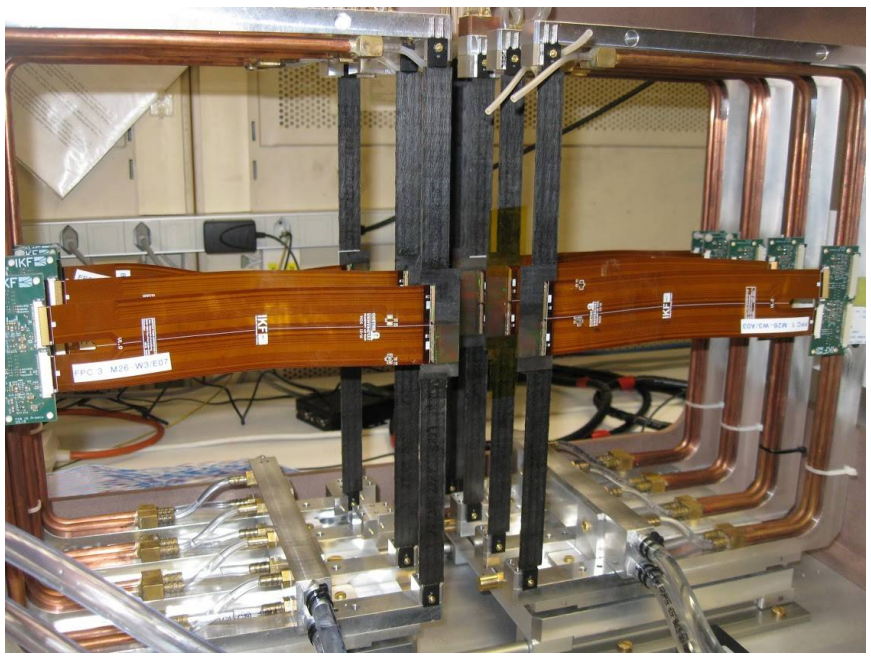
- NA61/SHINE performs the unique system size vs energy scan for **systematic study of the phase diagram of strongly interacting matter**
- Recent results of **NA61/SHINE and LHC** show some similarities between **p+p** and **Pb+Pb** hadron production
- **No** indication for **critical point so far**
- Unexpected system size dependence (in fluctuations and particle yields ratios) observed

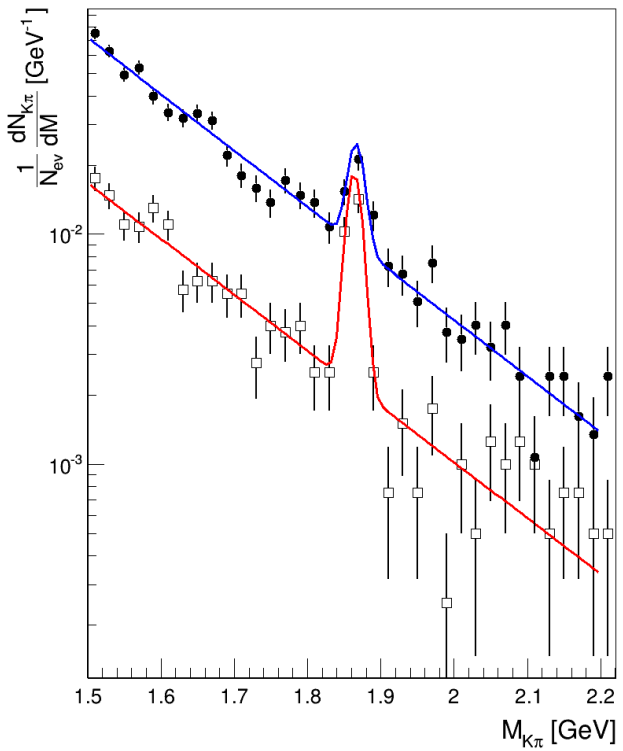




Outlook: NA61/SHINE in 2017-2018

- NA61/SHINE with new **Vertex Detector** will perform pilot **open charm measurements** and precise measurements of **fluctuations and collective effects** in Pb+Pb collisions[1]





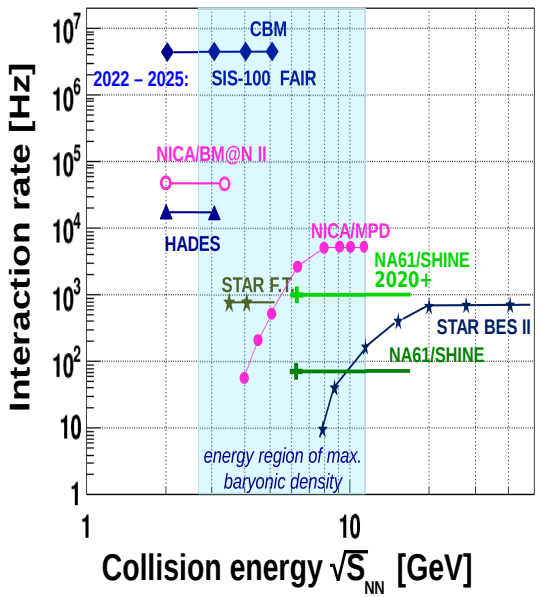
Invariant mass of pion-kaon pair candidates for D^0 signal. The results for realistic PID (open) and without PID (solid).

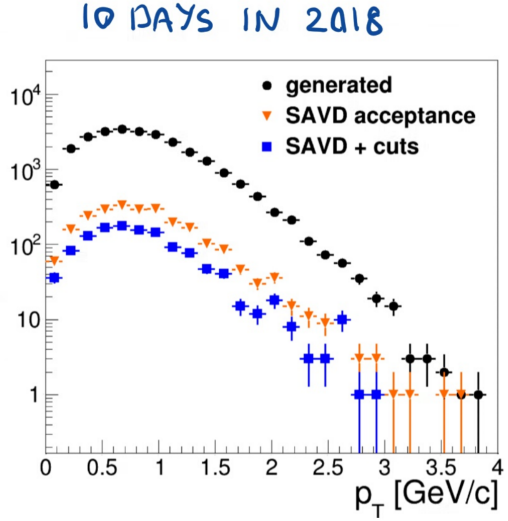
- The **2D scan will be completed** with **Xe+La this year** and **Pb+Pb** in 2018

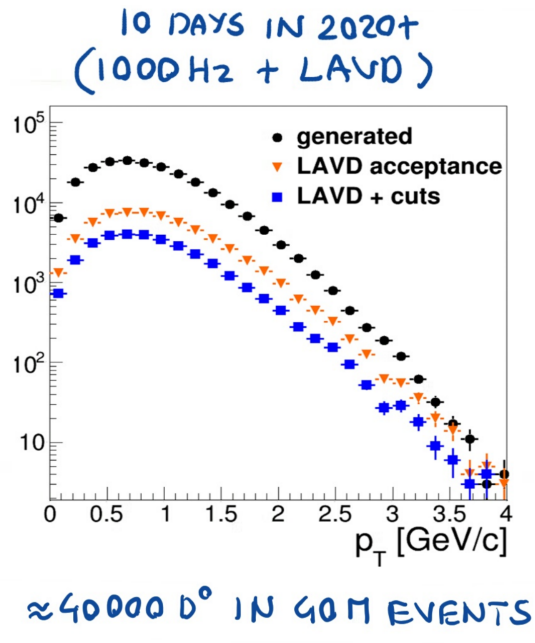
[1] Addendum to the NA61/SHINE program `http://cds.cern.ch/record/2059811`

Outlook: NA61/SHINE in 2021–2024

- **High statistics** beam momentum scan with **Pb+Pb** collisions for precise measurements of **open charm and multi-strange hyperon production**
- Detector upgrades during Long Shutdown in 2019–2020: **1 kHz readout**, **Large Acceptance Vertex Detector**, ToF, PSD







- NA61/SHINE conducts a **rich neutrino physics program** which is planned to be continued after 2020


WELCOME!
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Future Physics Opportunities with the NA61/SHINE Spectrometer
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SHINE
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Backup

NA61/SHINE Collaboration ∼150 physicists from ∼30 institutes

- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- Hungary
  - Wigner RCP, Budapest
- Japan
  - KEK Tsukuba, Tsukuba
- Norway
  - University of Bergen, Bergen
- Poland
  - UJK, Kielce
  - NCBJ, Warsaw
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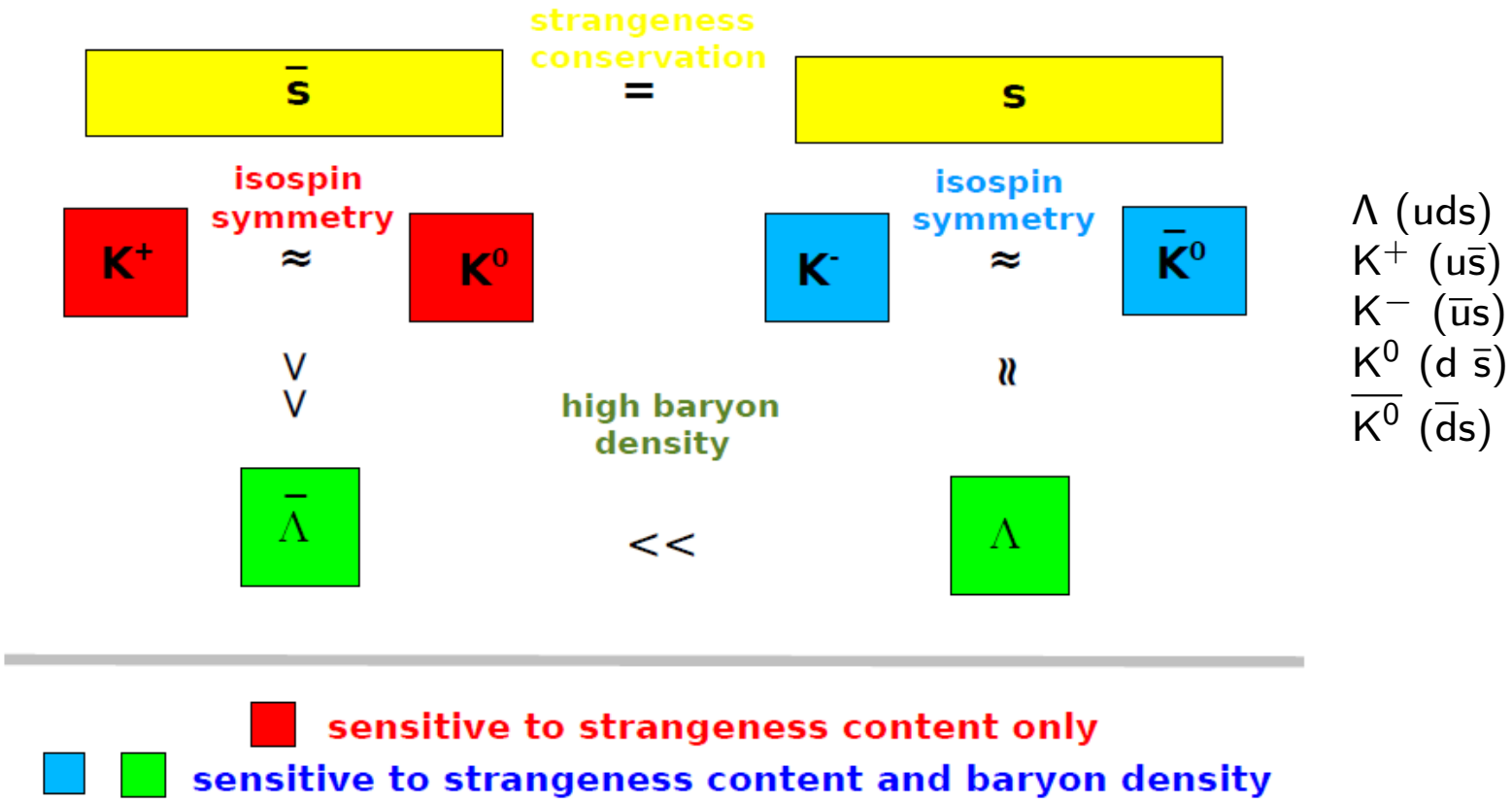
  - IFJ PAN, Kraków
  - AGH, Kraków
  - University of Silesia, Katowice
  - University of Wrocław, Wrocław
- Russia
  - INR Moscow, Moscow
  - JINR Dubna, Dubna
  - SPBU, St.Petersburg
  - MEPhI, Moscow
- Serbia
  - University of Belgrade, Belgrade
- Switzerland
  - ETH Zürich, Zürich
  - University of Bern, Bern
  - University of Geneva, Geneva
- USA
  - University of Colorado Boulder, Boulder
  - LANL, Los Alamos
  - University of Pittsburgh, Pittsburgh
  - FNAL, Batavia
  - University of Hawaii, Manoa

Publications from the NA61/SHINE two-dimensional scan

1. p+p collisions at 13, 20, 31, 40, 80, and 158 GeV/c
   - 1.1 π^- production in p+p at 20–158 GeV/c; based on h^- method [1]
   - 1.2 $\pi^\pm$, $K^\pm$, $\bar{p}$ production in p+p at 20–158 GeV/c; based on information from dE/dx and *tof*-dE/dx [2]; see also Ref. [3] for identified particle multiplicities in 4π
   - 1.3 Λ production in p+p at 40 [4] and 158 GeV/c [5]
   - 1.4 Transverse momentum and multiplicity fluctuations of non-identified hadrons in p+p at 20–158 GeV/c [6]; a new set of preliminary results for p+p in a slightly different acceptance was shown in Refs. [7, 8]
   - 1.5 Two-particle correlations of non-identified hadrons in azimuthal angle and pseudo-rapidity in p+p at 20–158 GeV/c [9, 10]
   - 1.6 Multiplicity fluctuations of identified particles (chemical fluctuations) in p+p at 31–158 GeV/c [11]; additional preliminary results on $\pi^+\pi^-$ fluctuations were shown in Refs. [12, 13]
   - 1.7 Higher order moments of multiplicity and net-charge fluctuations in p+p at 31–158 GeV/c [7, 14]
2. Be+Be collisions at 13A, 19A, 30A, 40A, 75A, and 150A GeV/c
   - 2.1 π^- production in Be+Be at 20–150A GeV/c; based on h^- method [15, 16]
   - 2.2 Cross-section in Be+Be at 13–150A GeV/c [15, 7] (Ref. [7] shows updated results and for all energies)
   - 2.3 $K^\pm$ spectra at mid-rapidity in Be+Be at 30–150A GeV/c (Ref: [17])
   - 2.4 Transverse momentum and multiplicity fluctuations of non-identified hadrons in Be+Be at 19–150A GeV/c [18, 7] (those two references show results in slightly different acceptances)
   - 2.5 Long-range correlations (in multiplicities and mean transverse momenta) in Be+Be at 150A GeV/c [19]
   - 2.6 Long-range fluctuations (in electric charge) in Be+Be at 150A GeV/c [20]

Publications from the NA61/SHINE two-dimensional scan

3. Ar+Sc collisions at 13A, 19A, 30A, 40A, 75A, and 150A GeV/c
   - 3.1 π^- production in Ar+Sc at 13–150A GeV/c; based on h^- method [21, 22, 7]
   - 3.2 Transverse momentum and multiplicity fluctuations of non-identified hadrons in Ar+Sc at 19–150A GeV/c [8, 7]
   - 3.3 Multiplicity and multiplicity-forward energy fluctuations in Ar+Sc at 19–150A GeV/c [23, 7]

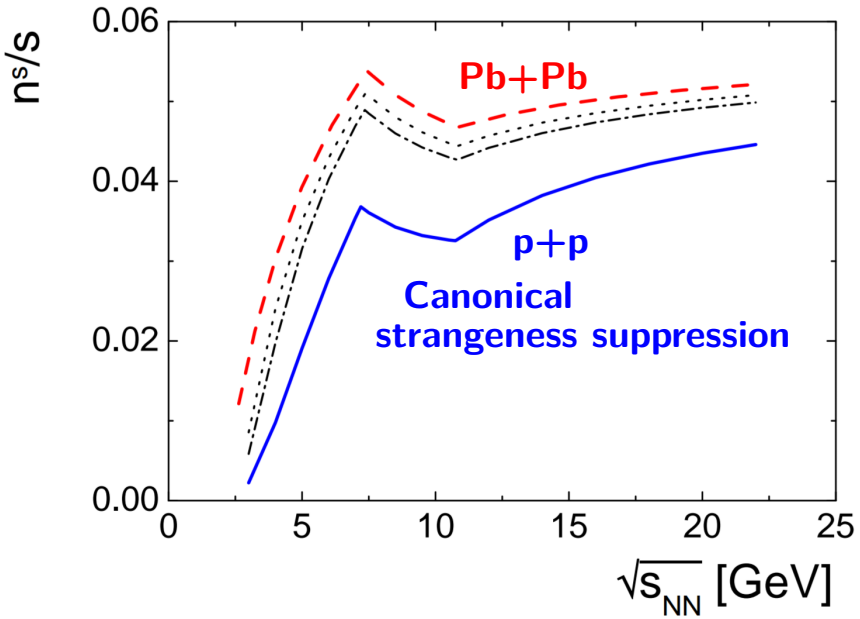


Λ (uds)
K^+ ($u\bar{s}$)
K^- ($\bar{u}s$)
K^0 ($d\ \bar{s}$)
$\overline{K^0}$ ($\bar{d}s$)

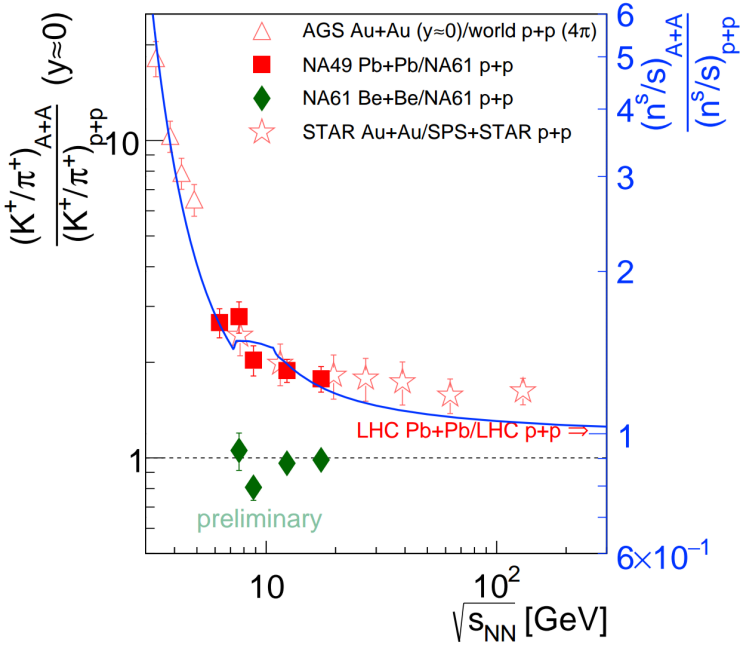
Difference in $\langle K^+ \rangle$ and $\langle K^- \rangle$ production due to different sensitivity to baryon density. At SPS energies lambdas have significant influence on total strangeness production ($\bar{\Lambda}$ not).

Study of the onset of deconfinement in p+p interactions

Statistical Model with phase transition (SMES):



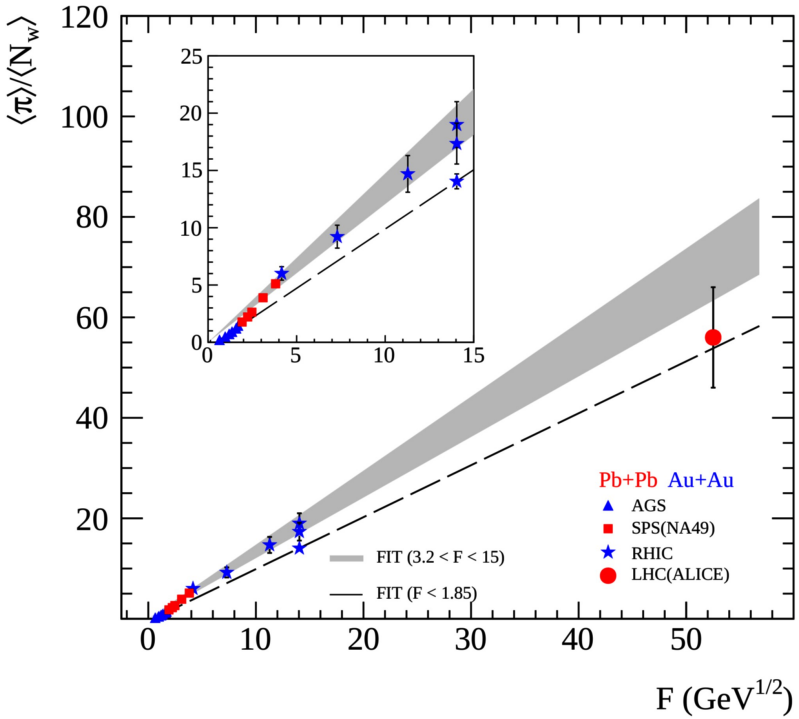
RVP, MG and MG, APP B46, 1991 (2015)



assumption: $K^+/\pi^+ = a(n_s/s) + b$

- Recent results of NA61/SHINE and LHC clearly suggest that p+p and Pb+Pb are qualitatively similar, e.g. rapid change of K^+/π^+ ratio at SPS energies and collective flow at LHC energies in p+p
- Be+Be interactions are very close to p+p

KINK in LCH energy range



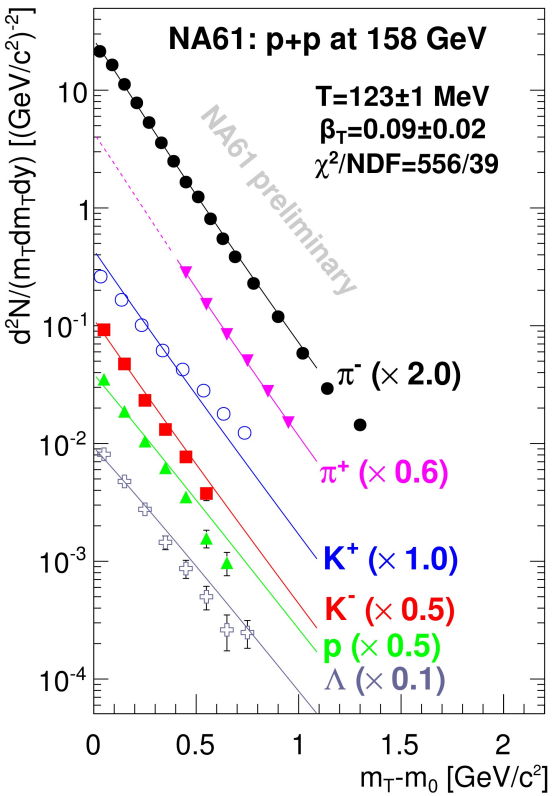
- Kink: increased entropy
- Pions measure early stage entropy.
- In SMES
  $< \pi > / < W > \sim (ndf)^{\frac{1}{4}}$
- Change of slope around $30A$ GeV$/c$
- No change of slope in p+p data (not shown)
- $< \pi >$ at LHC was estimated based on ALICE N_{ch} measurement

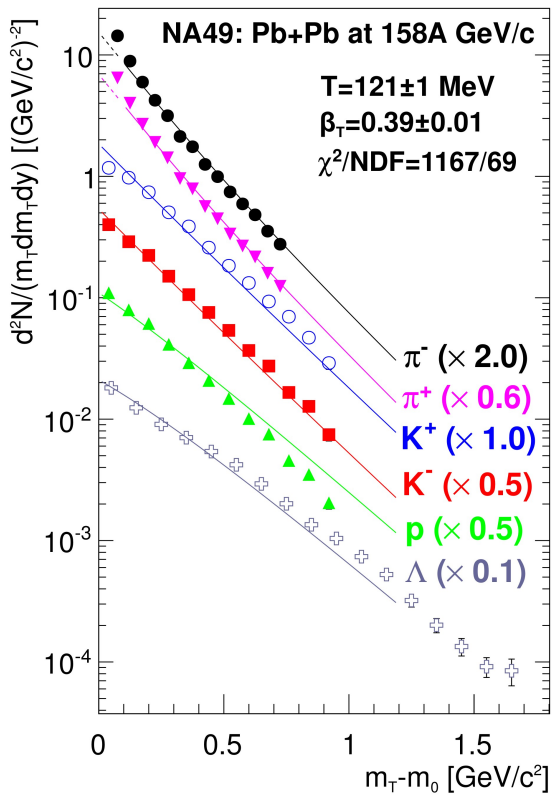
m_T spectra in p+p described with Blast Wave model

$$\frac{dN_i}{m_T\, dm_T\, dy} = A_i\, m_T\, K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right)$$

PR C48, 2462 (1993)

$$\rho = \mathrm{atanh}\,\beta_T$$



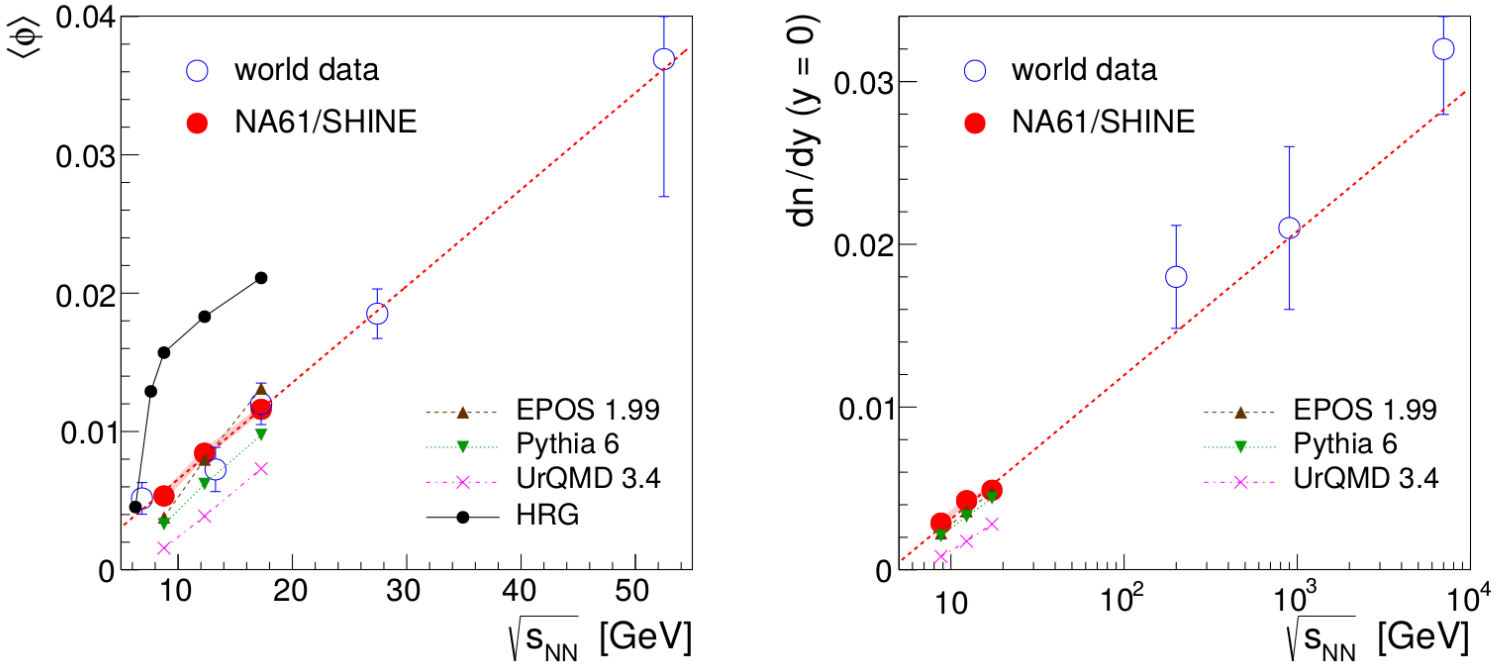


NA61/Shine
SPSC report 2014
and
arXiv:1510.00674

$$\frac{1}{p_T}\frac{dN}{dp_T} = \frac{1}{m_T}\frac{dN}{dm_T}$$

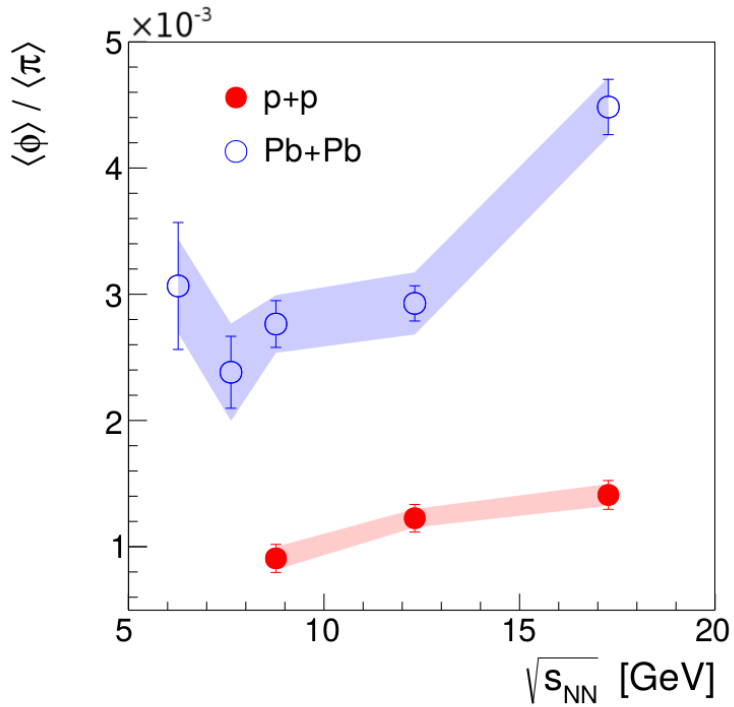
- Transverse mass spectra are approximately exponential

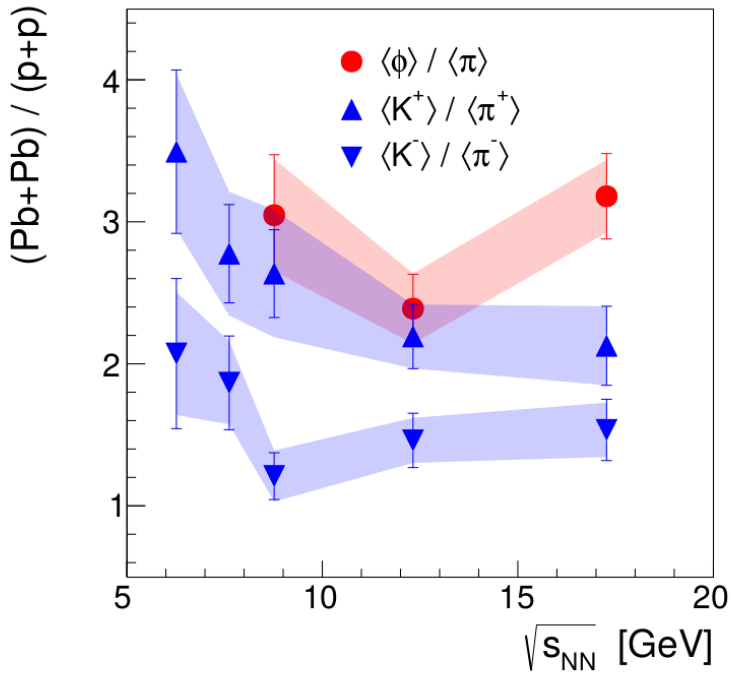
Reference data for heavy ions: ϕ production



- $\langle\phi\rangle$ results in p+p interactions at $\sqrt{s_{NN}} = 8.7, 12.3$(first measurements) and 17.3 GeV
- results consistent with world data
- EPOS close to data, Pythia underestimates experimental data, UrQMD underestimates $\sim 2\times$, HRG (thermal) overestimates $\sim 2\times$
- EPOS rises too fast with interaction energy

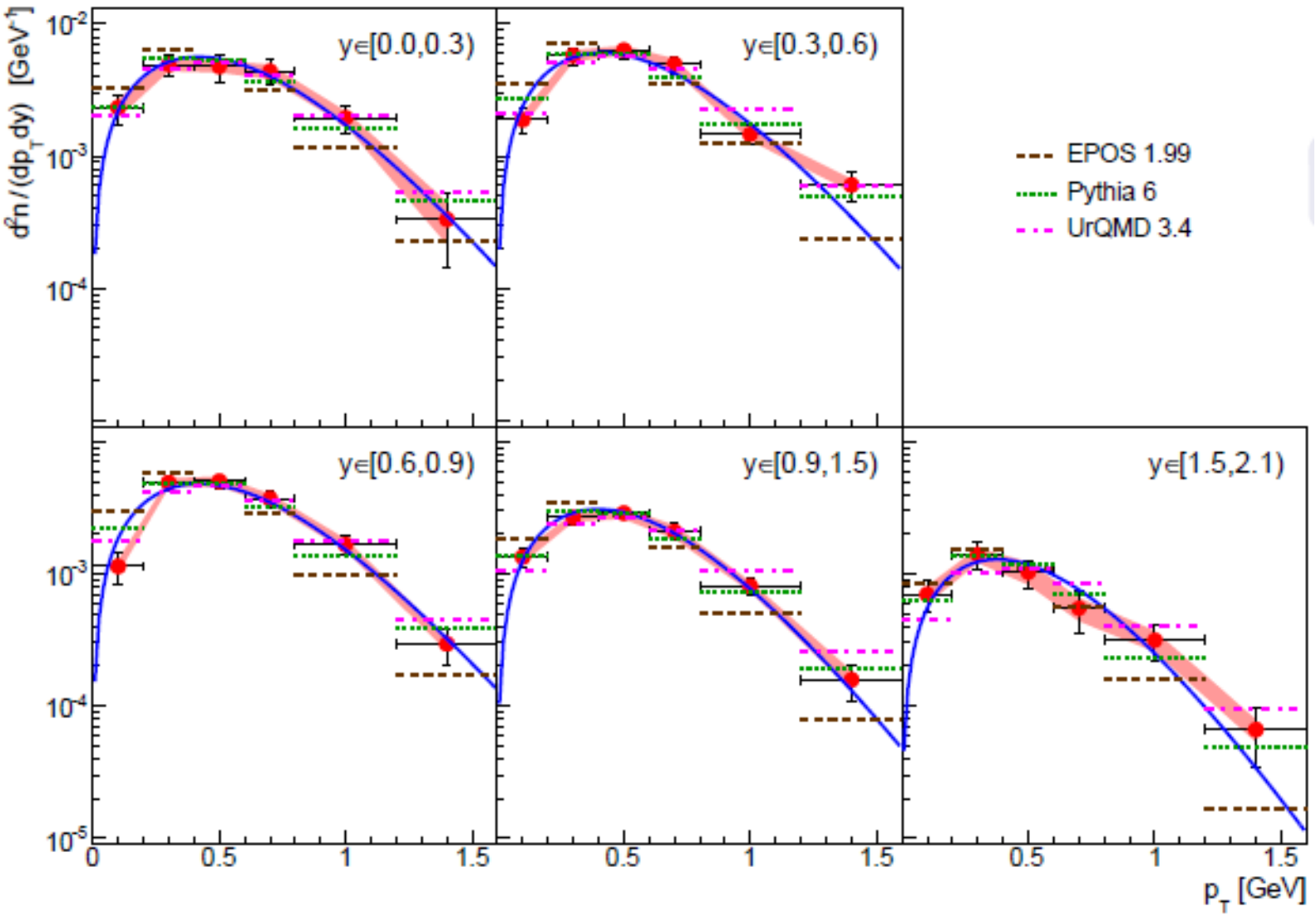
Reference data for heavy ions: ϕ production



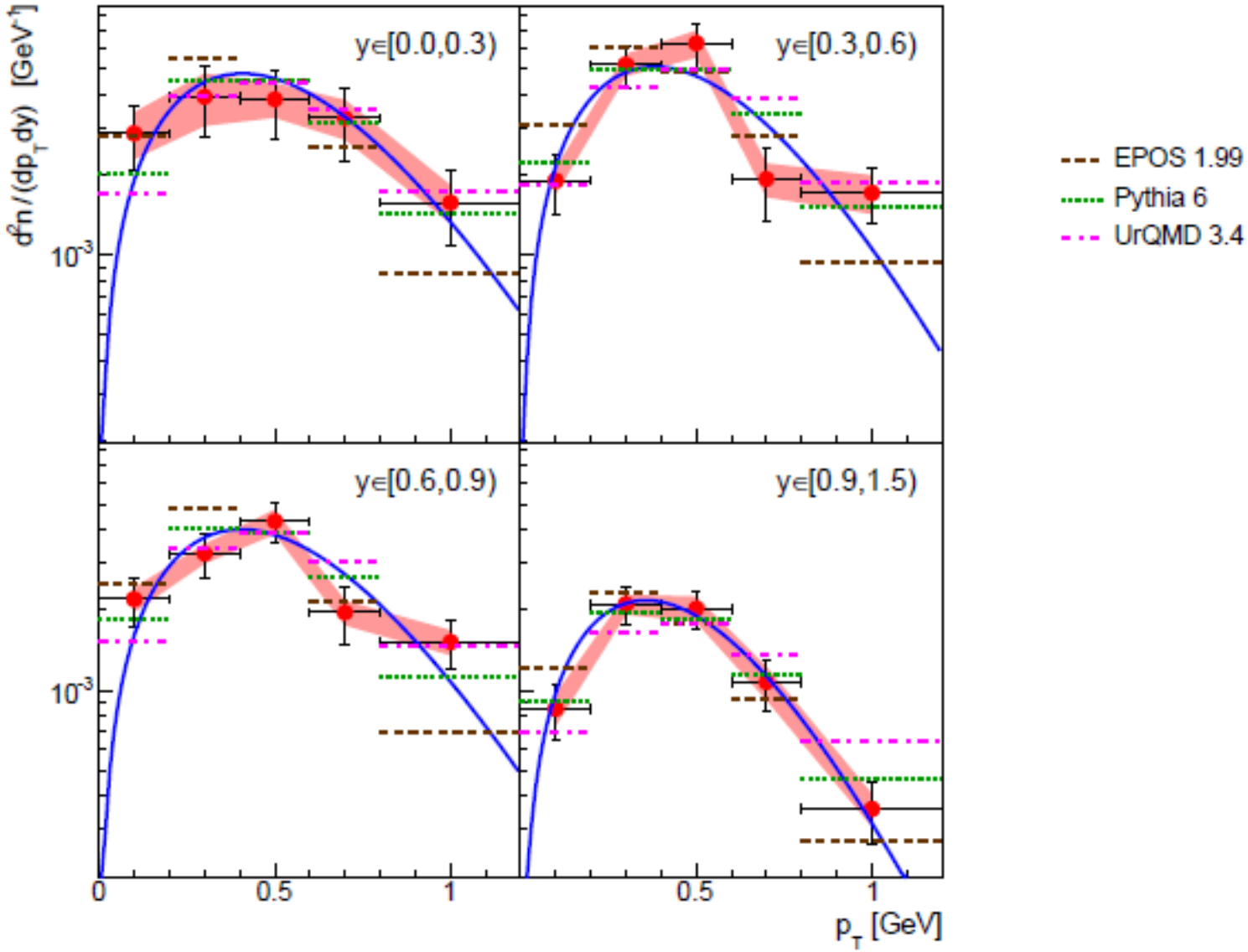


- $\langle\phi\rangle/\langle\pi\rangle$ increases with $\sqrt{s_{NN}}$
- production of $\langle\phi\rangle/\langle\pi\rangle$ in Pb+Pb collisions about 3$\times$ larger independently of interaction energy
- Enhancement of $\langle\phi\rangle/\langle\pi\rangle$ is systematically larger than for $\langle K^-\rangle/\langle\pi^-\rangle$ and comparable with $\langle K^+\rangle/\langle\pi^+\rangle$

ϕ spectra at 158 GeV/c

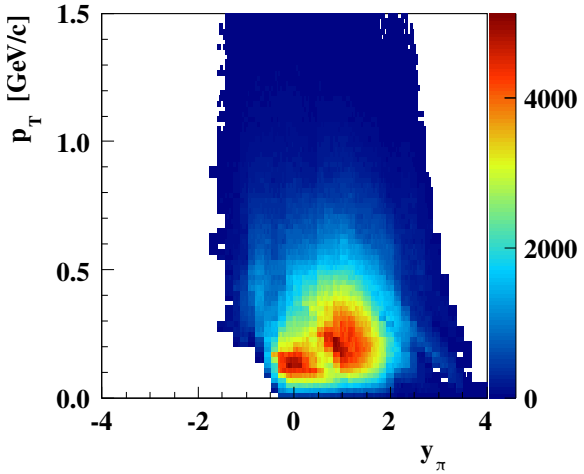


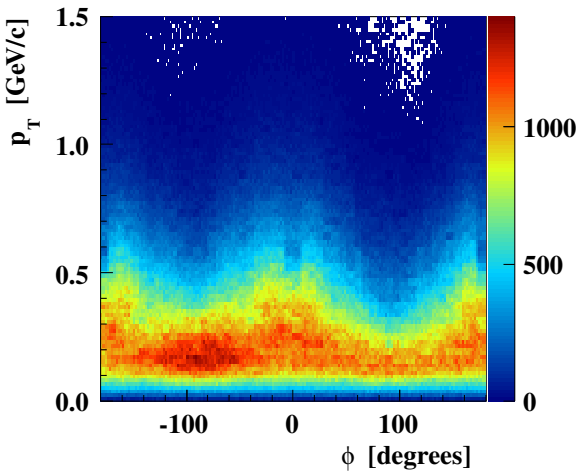
ϕ spectra at 80 GeV/c



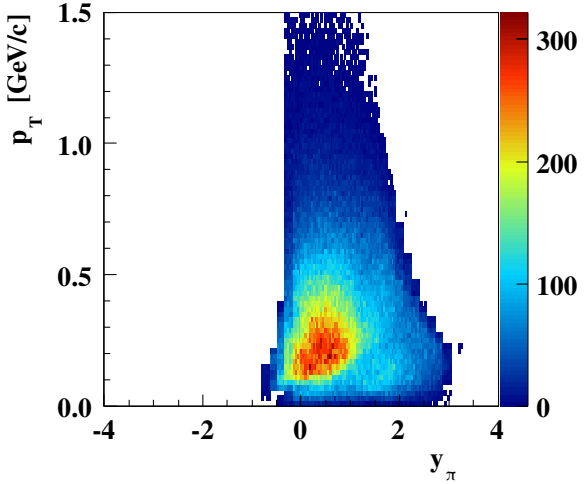
Acceptance of fluctuation analysis in p+p 20 and 158 GeV/c

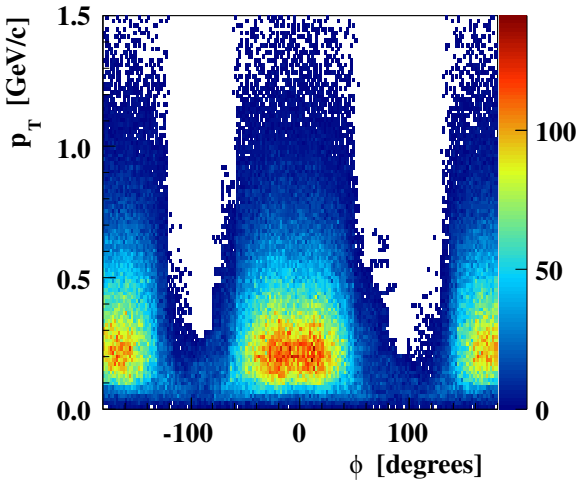
Acceptance for 150A GeV/c momentum



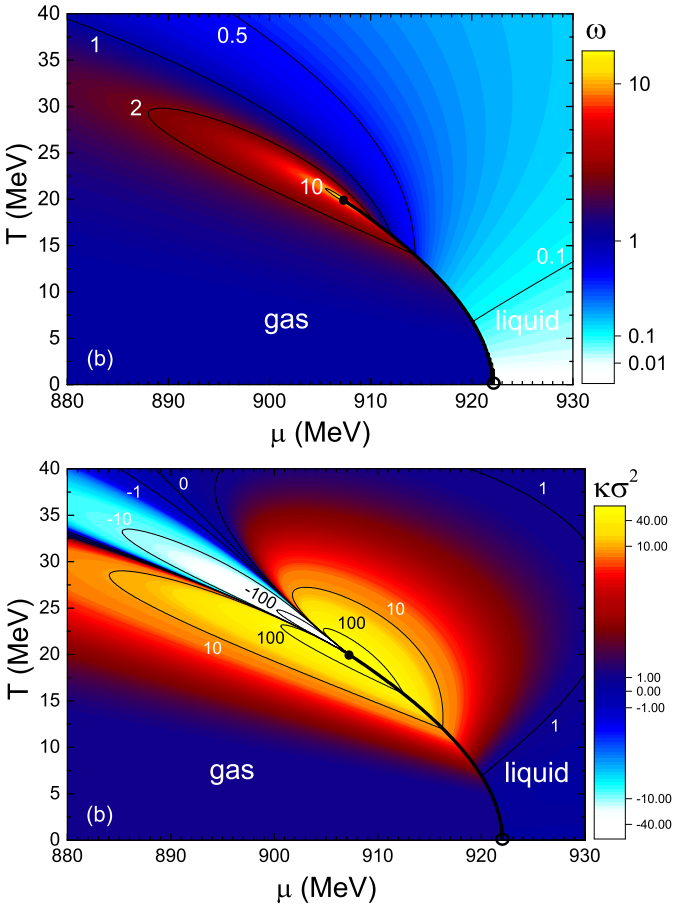


Acceptance for 20A GeV/c momentum





Search for the critical point



GCE calculation within the Van der Waals model of nuclear matter. V. V. et al., Phys.Rev. C92, 054901

- NA61/SHINE searches for the critical point by studying fluctuations e.g. by studying multiplicity and transverse momentum fluctuations.
- In order to study phase diagram systems of different sizes are used. Moreover, it is experientially not possible to fix volume fluctuations even for a given energy and system

↓

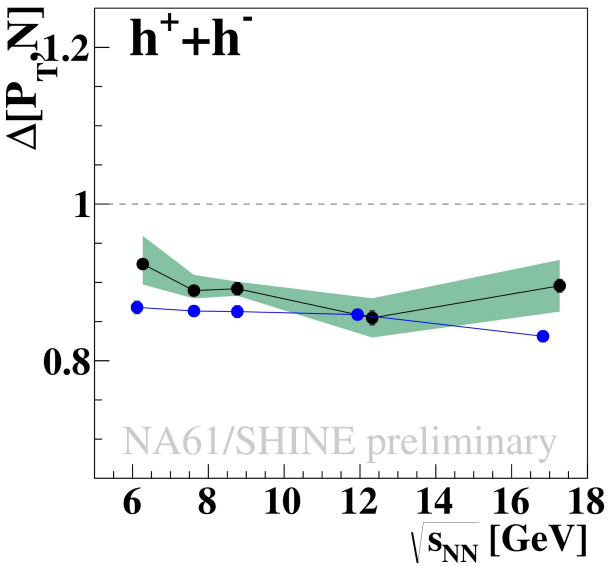
Used measures need to remove system size dependence (and its fluctuations):

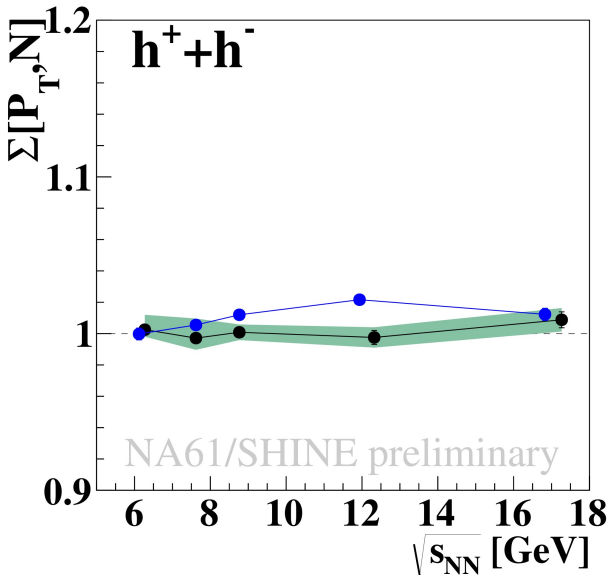
  - intensive quantities: ω, $\langle N^3 \rangle_c / Var[N]$ and $\langle N^4 \rangle_c / Var[N]$
  - strongly intensive quantities: $\Sigma[P_T, N]$ and $\Delta[P_T, N]$[a]

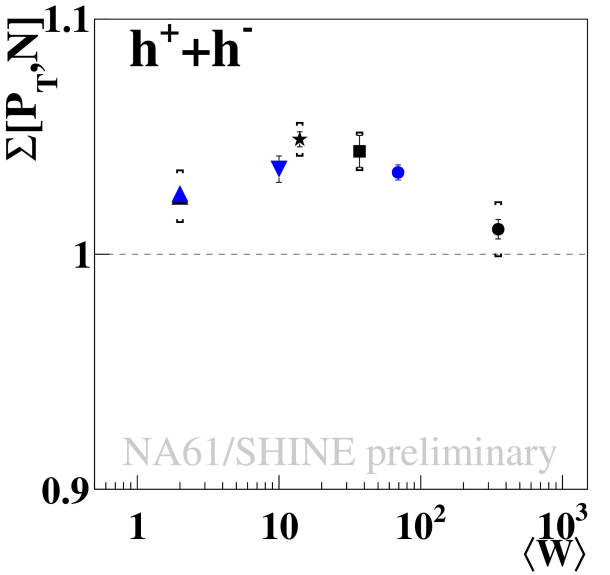
- **Fluctuations of unidentified hadrons are performed in forward hemisphere**
(for details see EPJ C76, 635 (2016))

[a] P_T is a sum of p_T of all particles in an event

Search for critical point: comparison with NA49

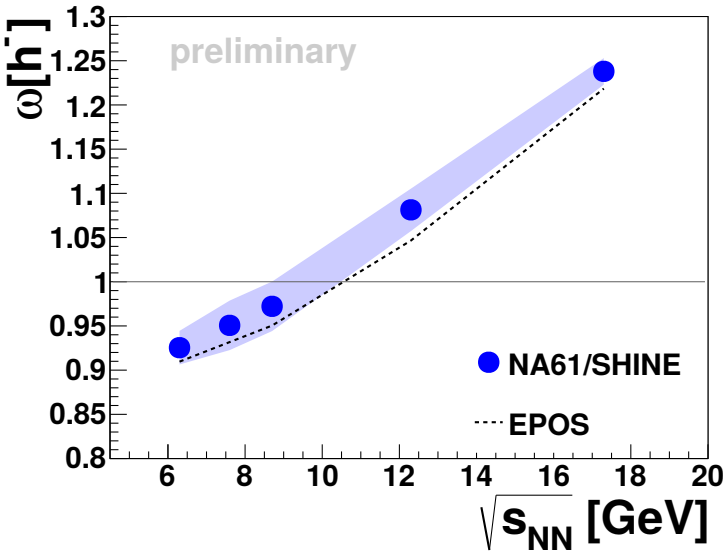


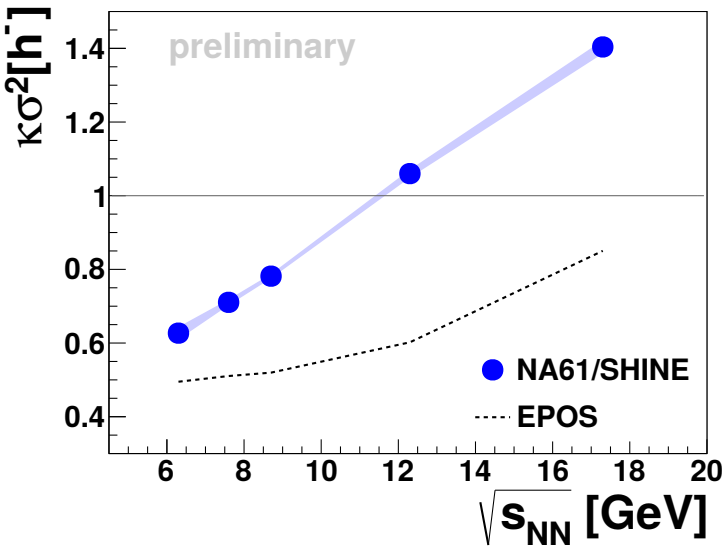


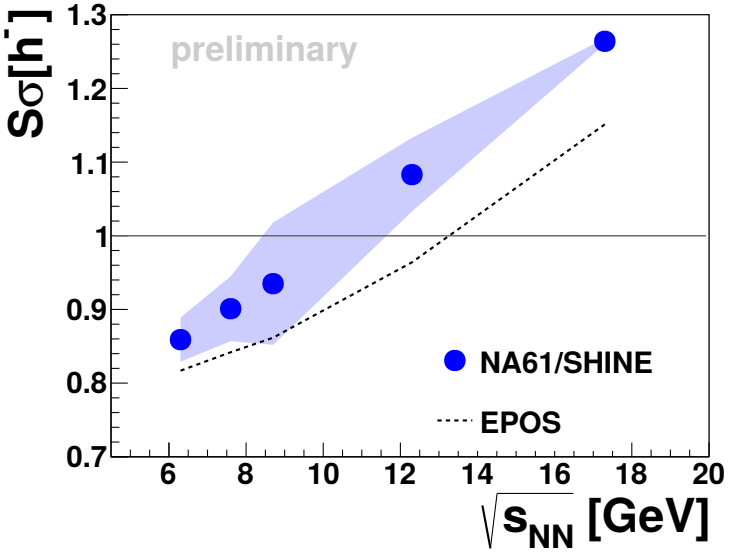


- comparison in **NA49 acceptance**: $1.1 < y_\pi < 2.6$, $y_p < y_{beam} - 0.5$
- Energy scan: NA49 **Pb+Pb** and NA61 **Ar+Sc results are similar**
- System size scan of $\Sigma[PT, N]$ at 150/158A GeV/c - **both experiments measure consistent trends**

Search for critical point: higher order moments in p+p

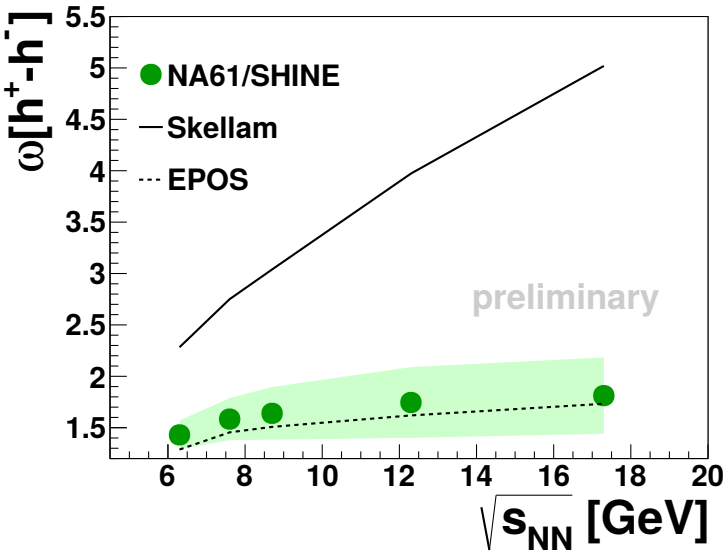


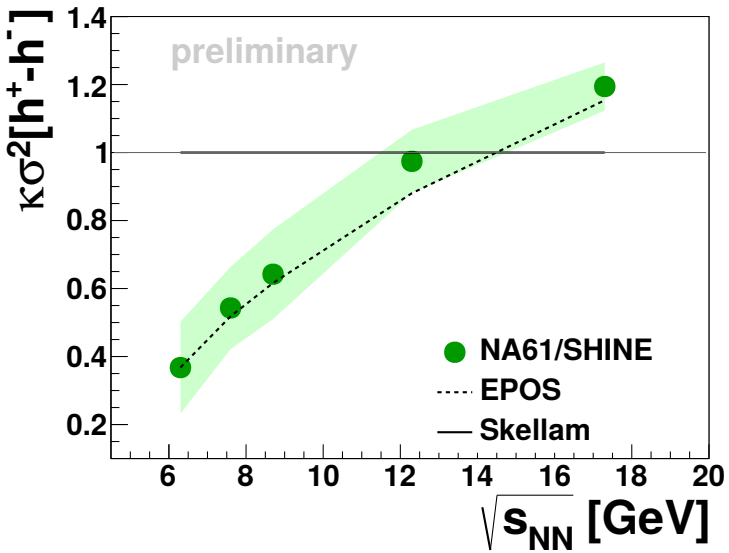


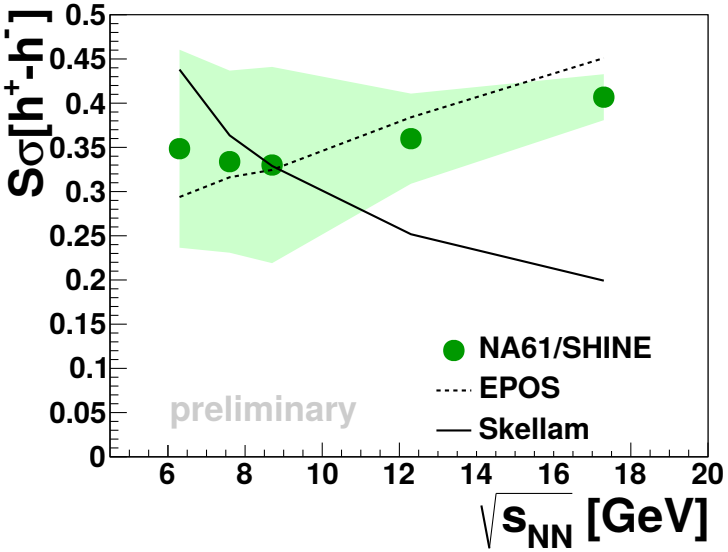


- NA61/SHINE acceptance (for details see EPJ C76, 635 (2016))
- all quantities rise with collision energy
- **magnitude of $\kappa\sigma^2$ is not reproduced by EPOS 1.99** within the acceptance

Search for critical point: higher order moments in p+p

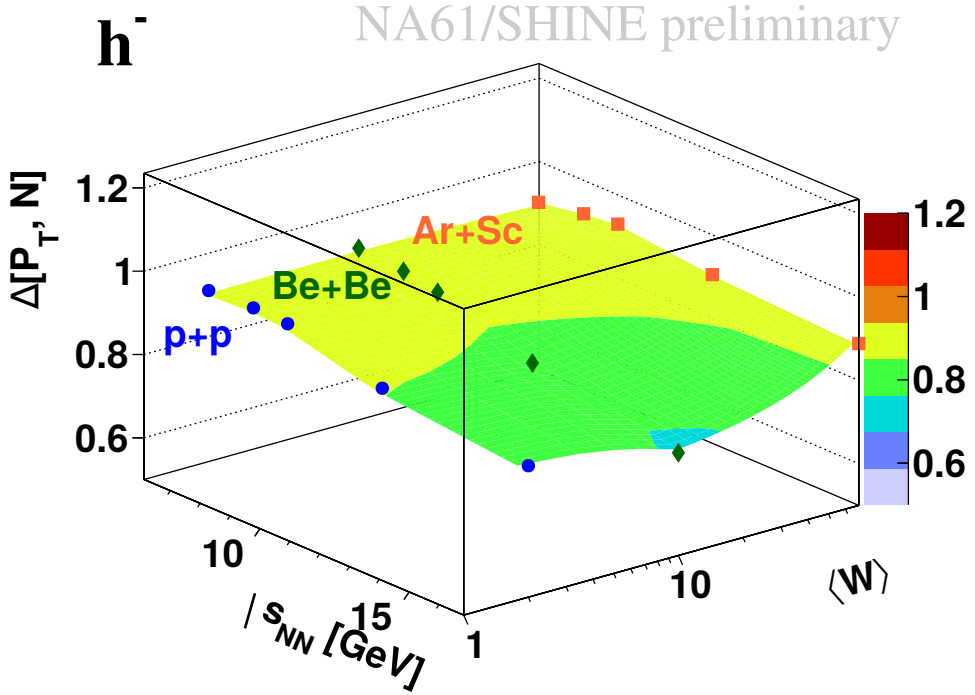






- NA61/SHINE acceptance (for details see EPJ C76, 635 (2016))
- results do not agree with independent particle production (Skellam)
- **EPOS 1.99 describes data**

Search for critical point: P_T and N fluctuations



Negatively charged hadrons in central A+A and inelastic p+p

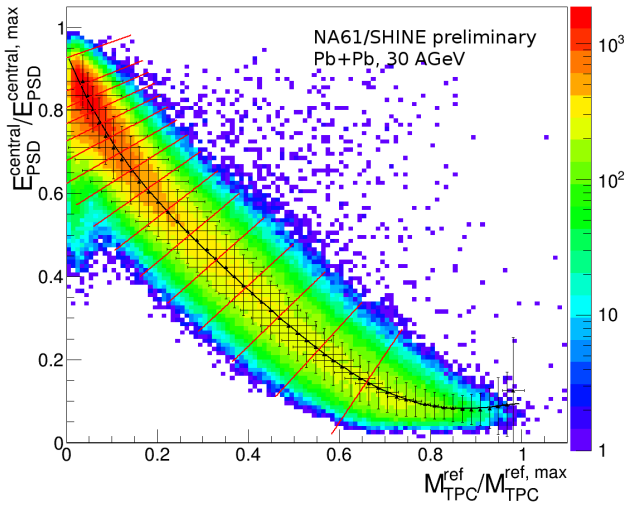
- Small monotonic decrease of $\Delta[P_T, N]$ with the collision energy
- **No indication for critical point so far**

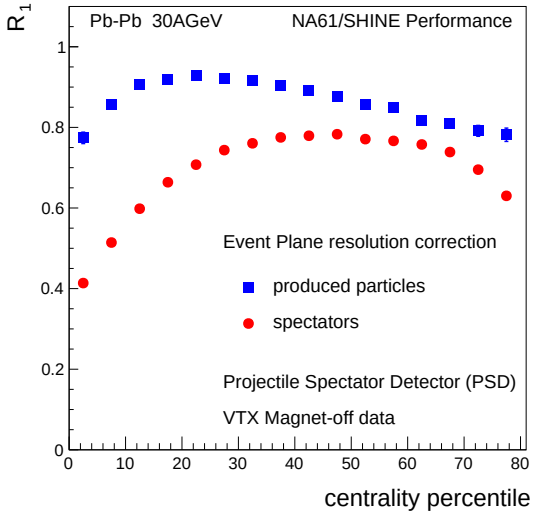
$$\Delta[A,B] = \frac{1}{C_\Delta}\left[\langle B\rangle\omega_A - \langle A\rangle\omega_B\right]$$

$\Delta[P_T, N] = 0$ for $N = \text{const.}$, $P_T = \text{const.}$
$\Delta[P_T, N] = 1$ for Independent Particle Model

Event plane

- NA61/SHINE attempts to measure **event plane** as well as direct flow





- Inspite of the **non-uniform azimuthal acceptance** measurements will benefit from **transversal and longitunal granularity of the forward calorimeter**

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